A WISH come true:

Water observations with Herschel

Ewine F. van Dishoeck
Leiden Observatory/MPE

www.strw.leidenuniv.nl/WISH

RCW120
Herschel
A. Zavagno

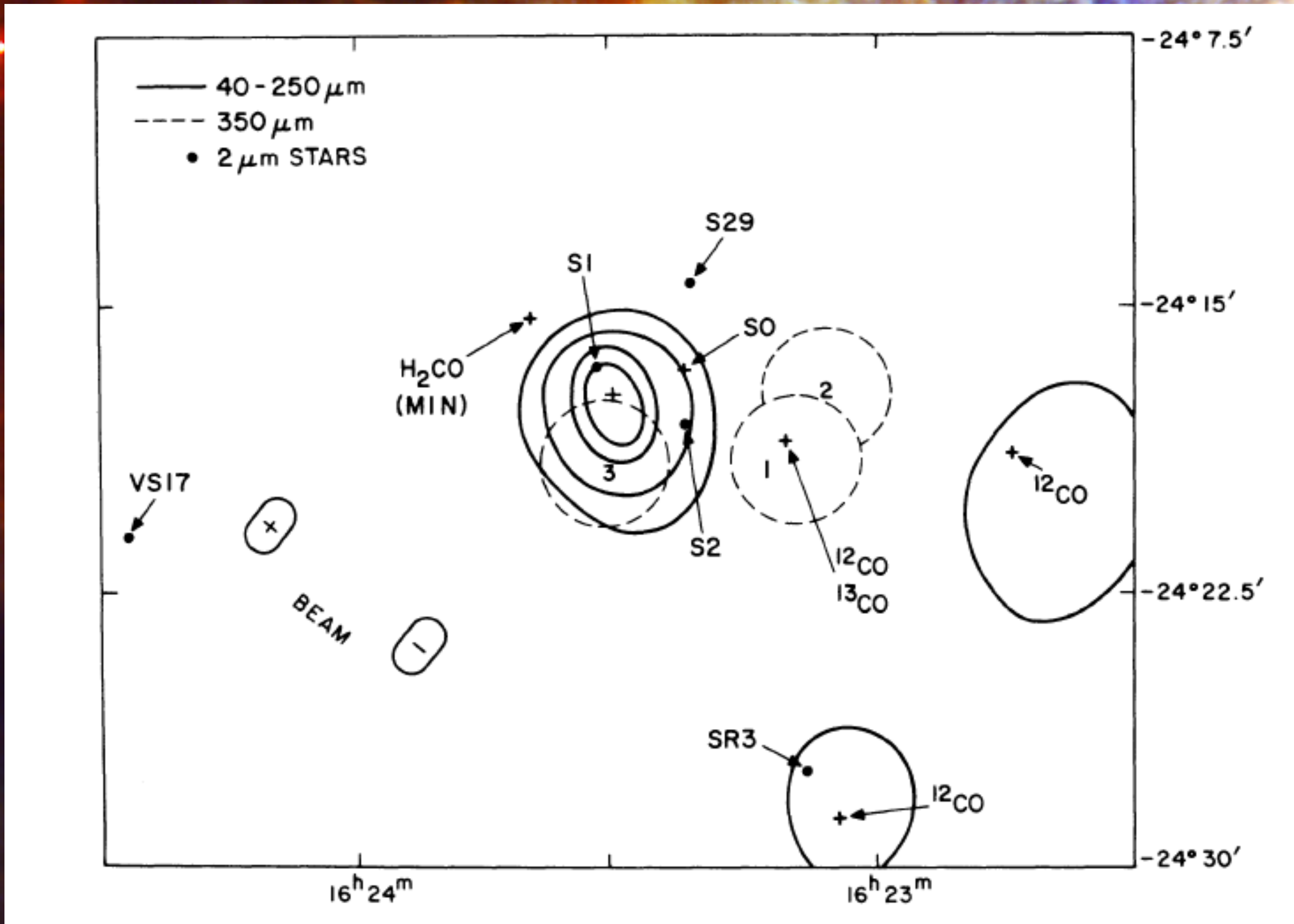
Herschel Space Observatory

3.5 m
~20” at 1 THz

Launch May 14, 2009

- HIFI
  - 490-1250 GHz; 1410-1910 GHz (~500-150 μm)
  - R~10^7; single pixel
- PACS
  - Photometer 55-210 μm
  - Imaging spectrometer
    - 5x5 pixels 9.4’’
    - R=1500-4000
- SPIRE
  - Photometer 194-672 μm
  - FTS R=50-1000 19-37 pixels over 2’ field; ~20-40’’ pixels

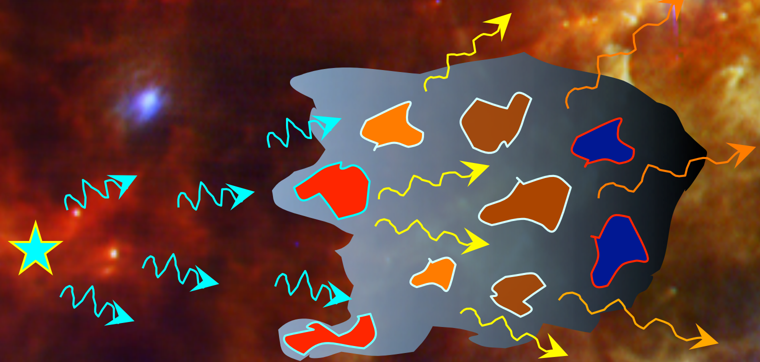
Herschel: we have come a long way

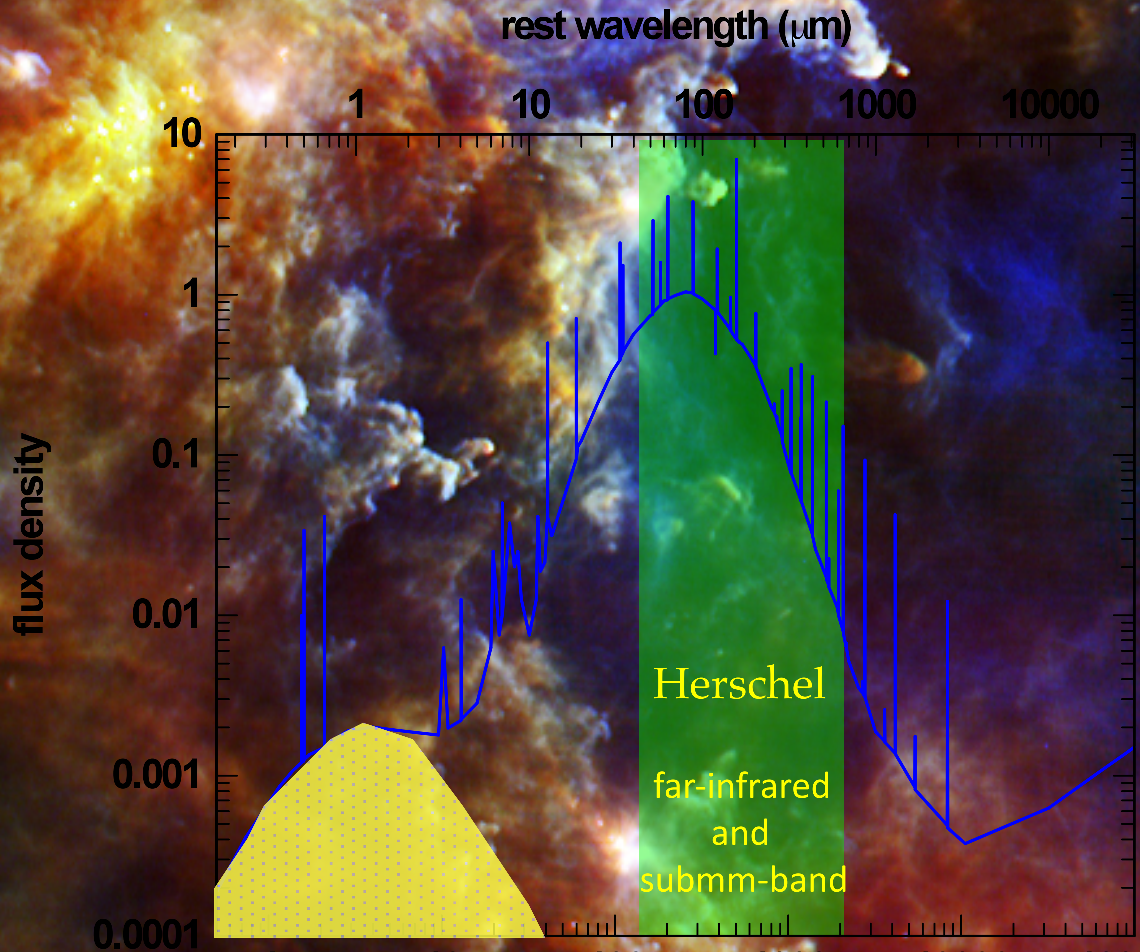


100μm map of the ρ-Oph star forming cloud: Fazio et al. 1976 (submm: Mezger et al. 1984)

Rosette molecular cloud PACS & SPIRE 70-350 μm Motte et al. 2010

The cool, dusty universe and star formation

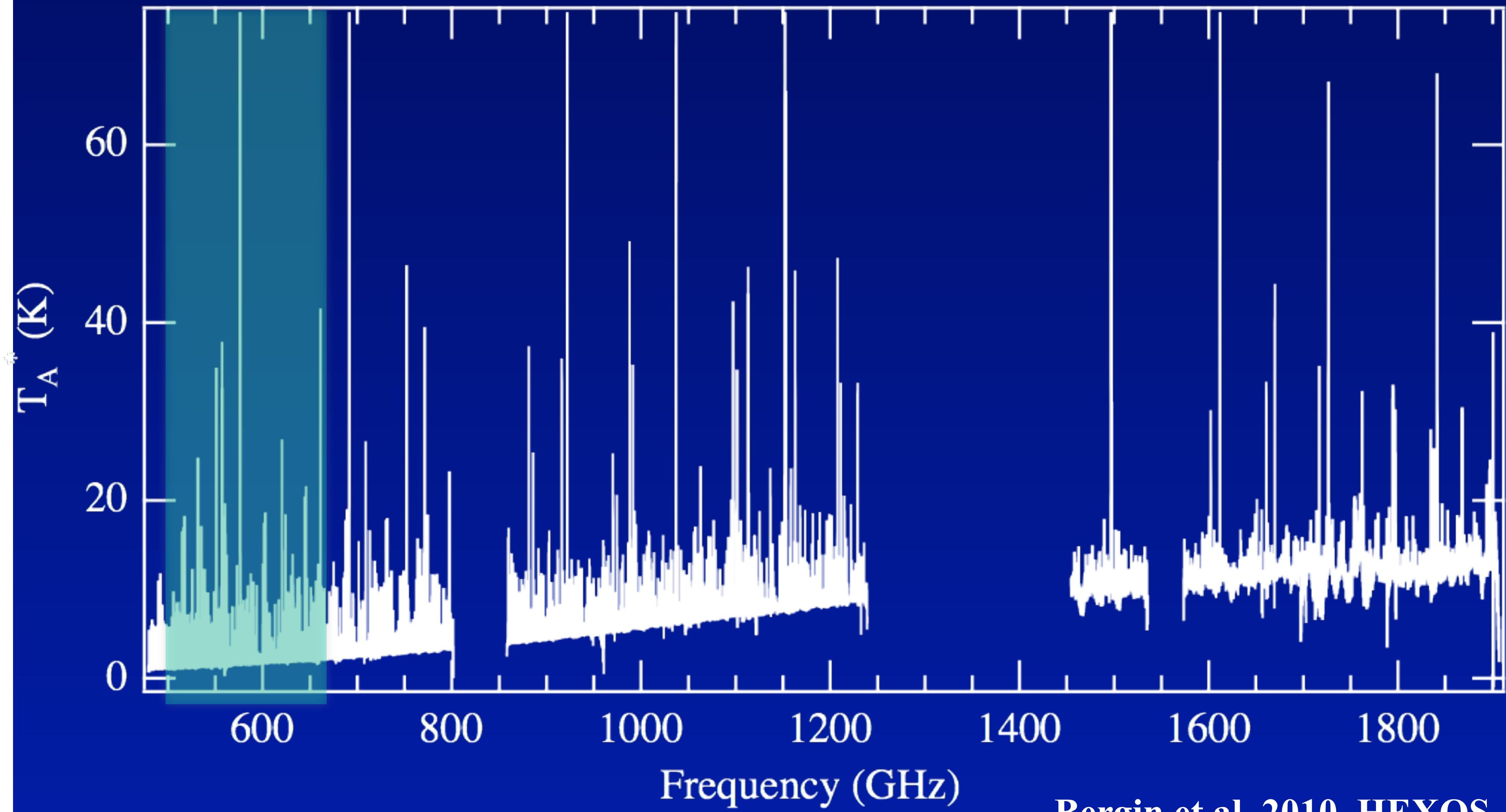




Conversion of X-/UV-radiation into far-infrared emission at the interface of a dense cloud

Genzel et al. 1992

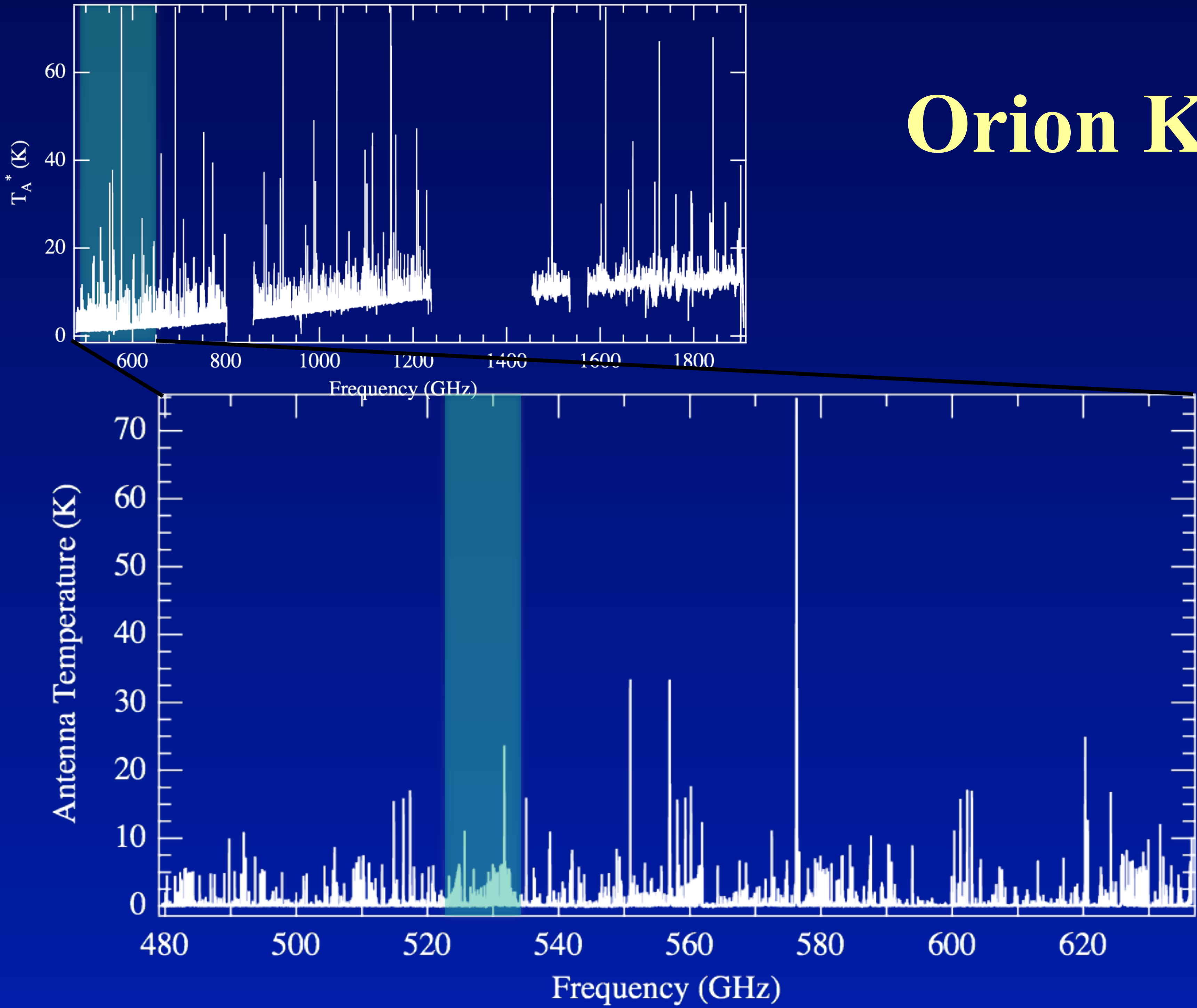
HIFI forest of lines in Orion



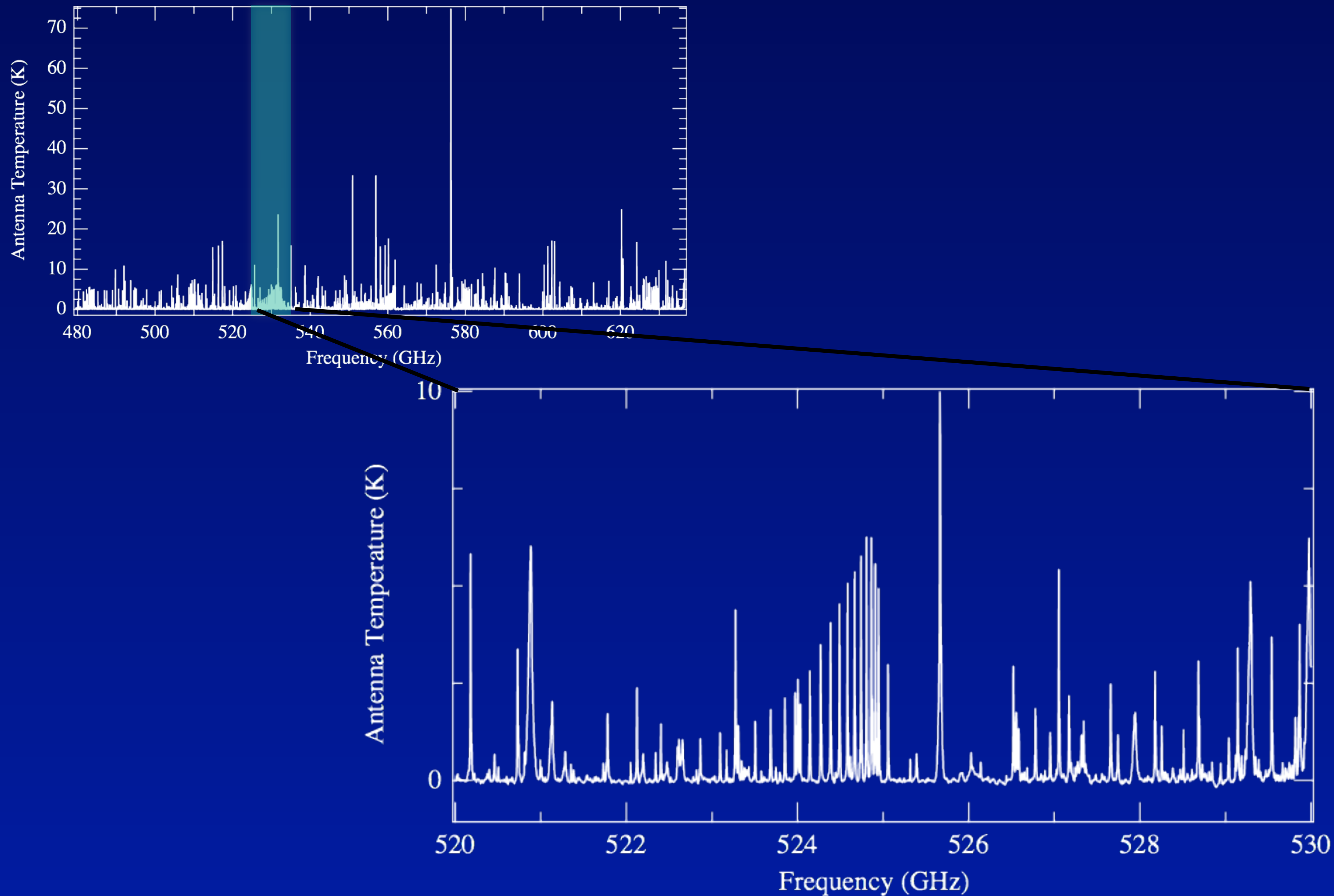
Bergin et al. 2010, HEXOS

Entire spectrum in just tens of hours!

Orion KL

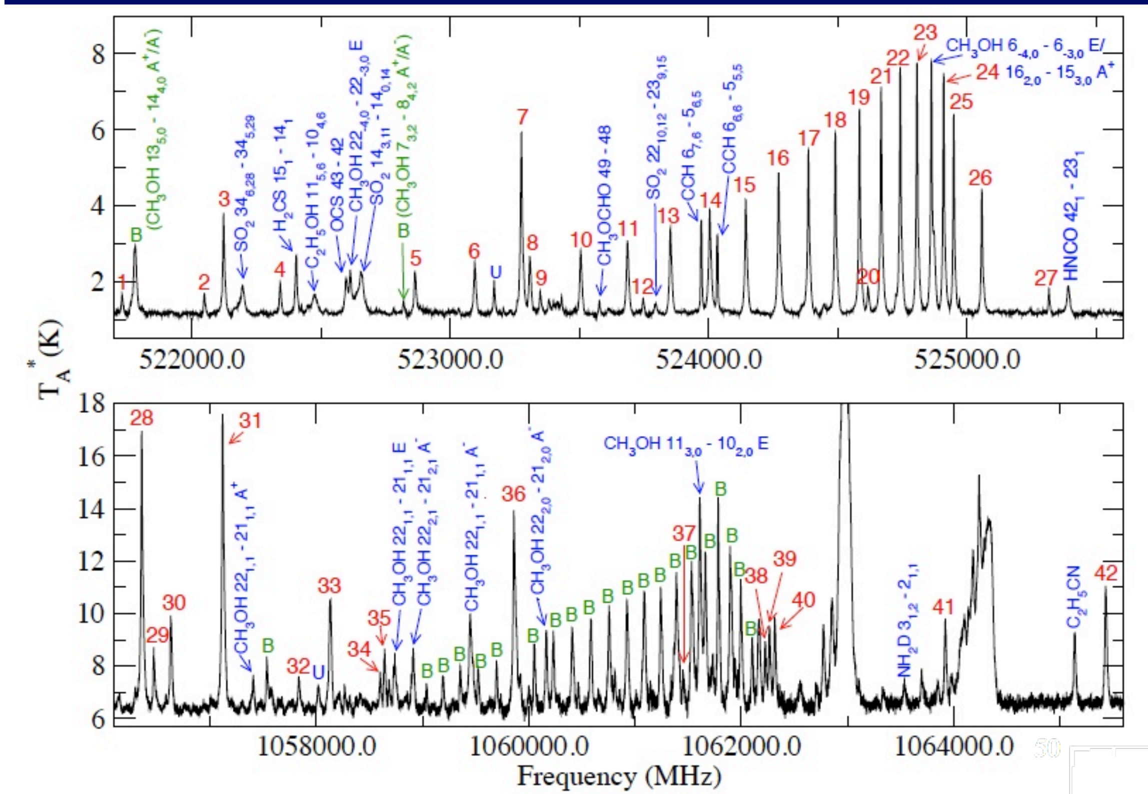


T_A^* (K)
0
20
40
60
600
800
1000
1200
1400
1600
1800
Frequency (GHz)
Antenna Temperature (K)
0
10
20
30
40
50
60
70
480
500
520
540
560
580
600
620
Frequency (GHz)



Orion KL - Band 1

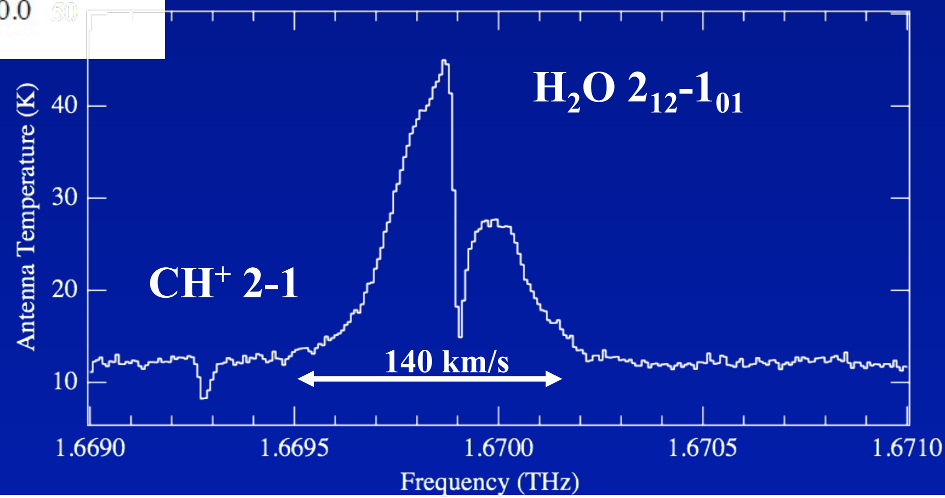
Herschel spectroscopy: we have come a long way



Orion-KL
HEXOS

Wang, Bergin et al. 2010

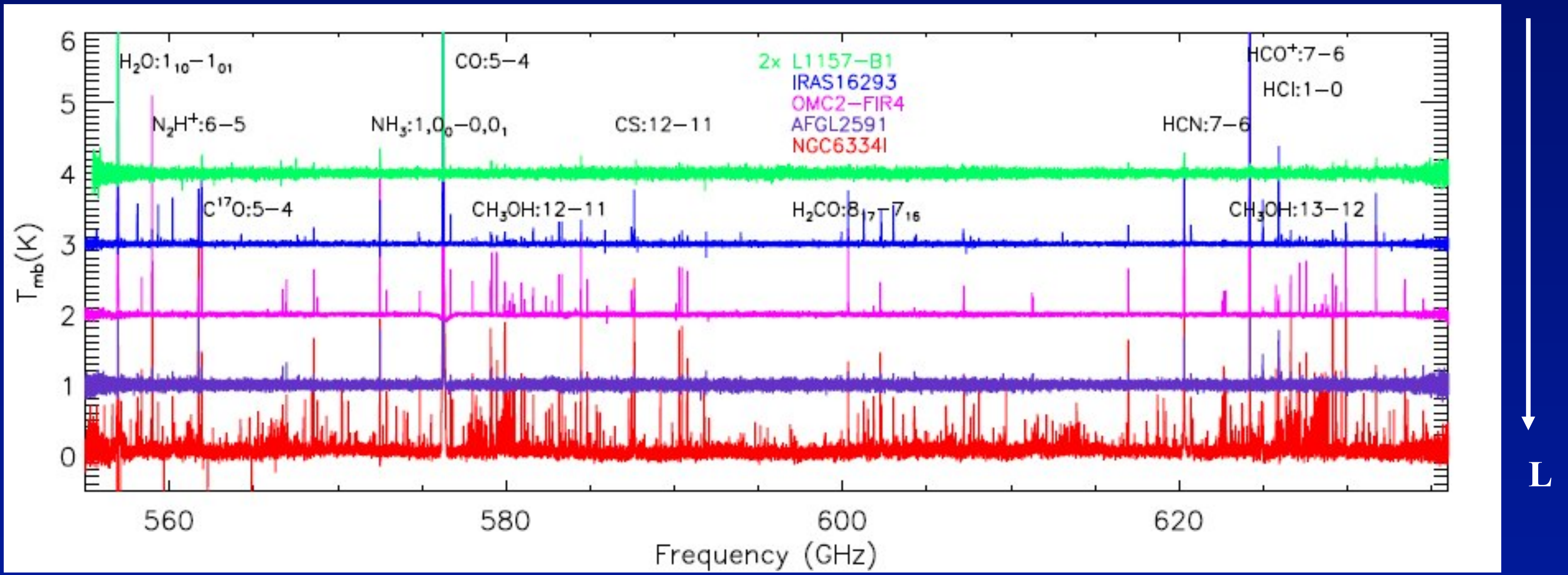
High-quality line profiles, even at 1.67 THz!



Crockett et al. 2010

HIFI spectral surveys: other sources

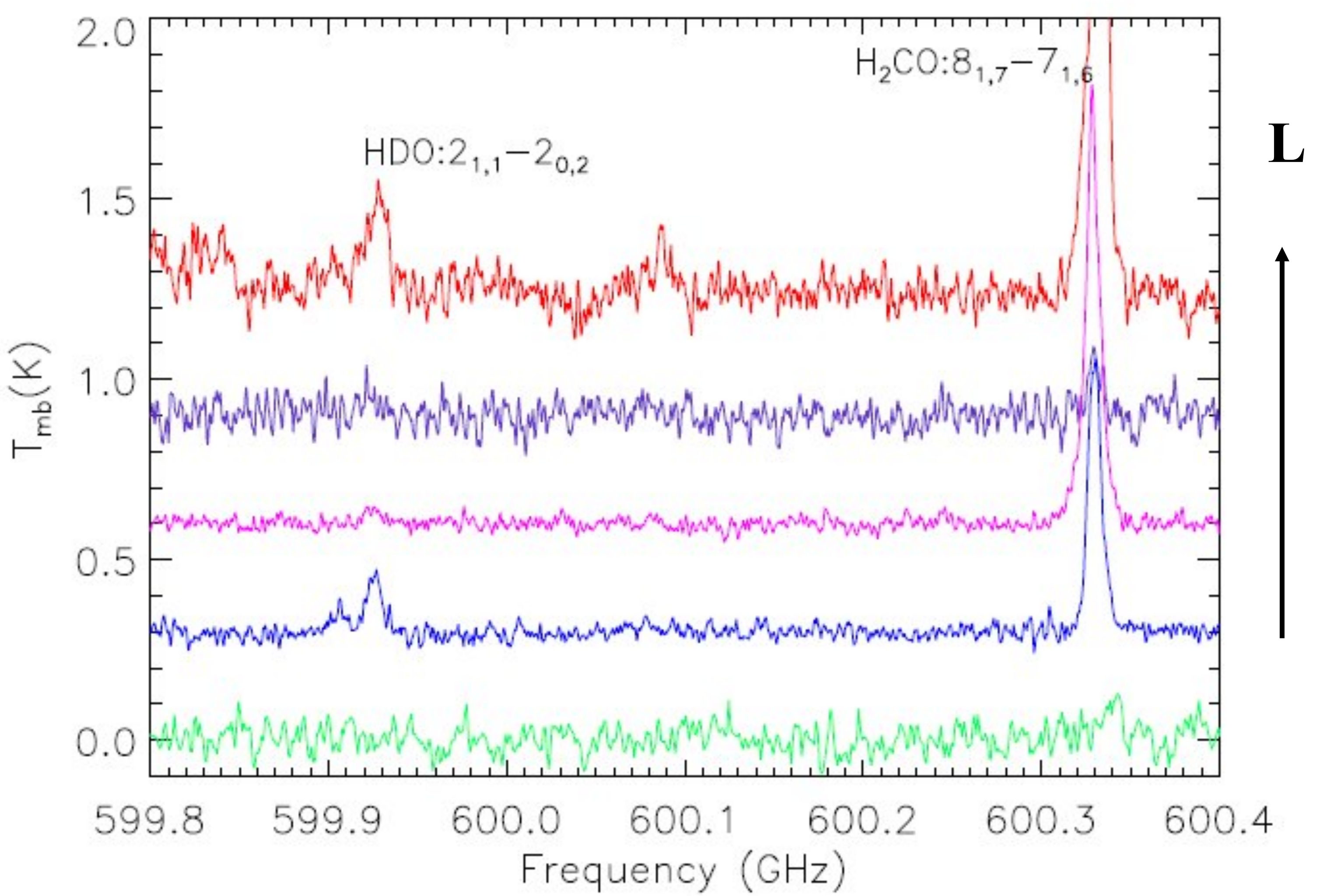
CHESS



Ceccarelli et al. 2010
Kama et al. 2010

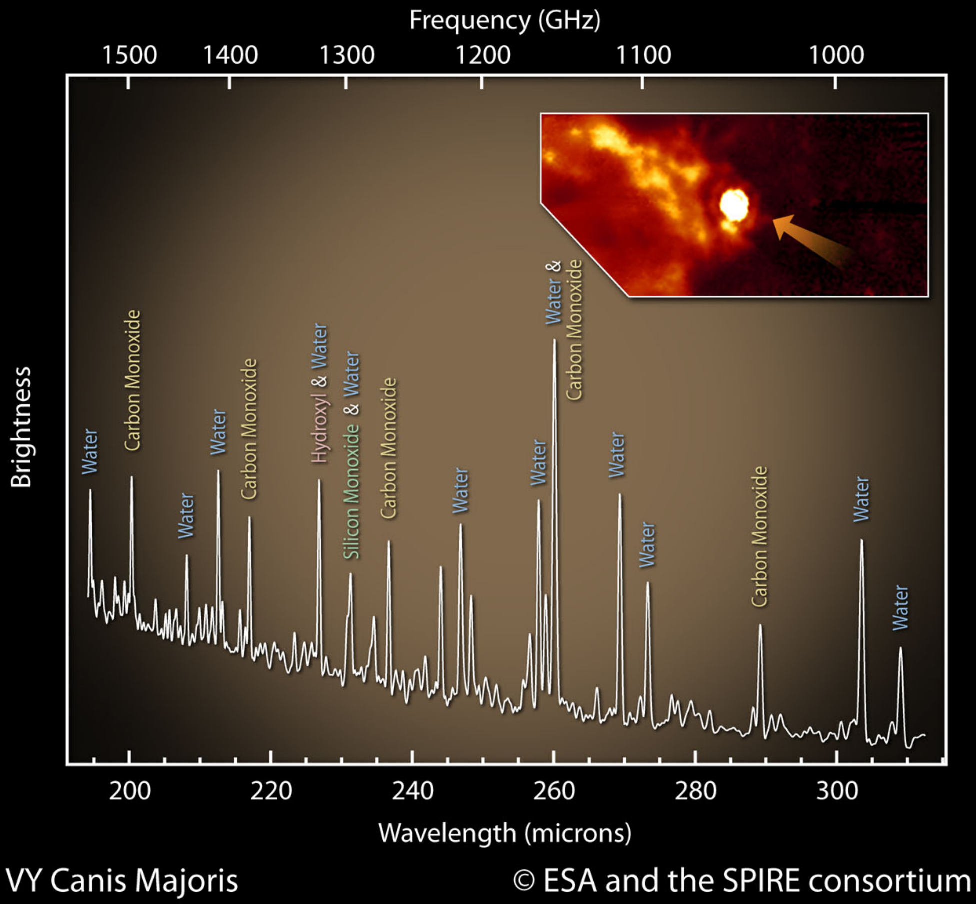
HIFI spectral surveys: zoom in

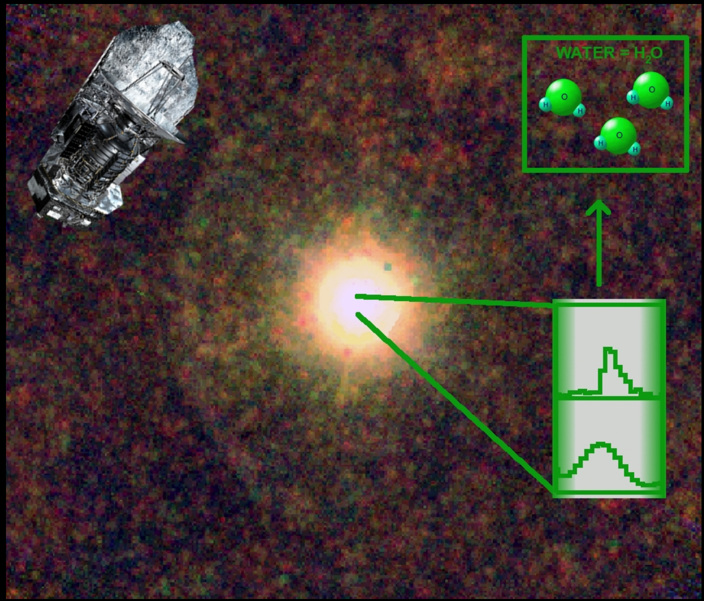
HDO



Ceccarelli et al. 2010

PACS and SPIRE spectral surveys





Hot water in oxygen- and carbon (!) -rich envelopes

Decin et al. 2010, Nature

Main strengths of Herschel spectroscopy

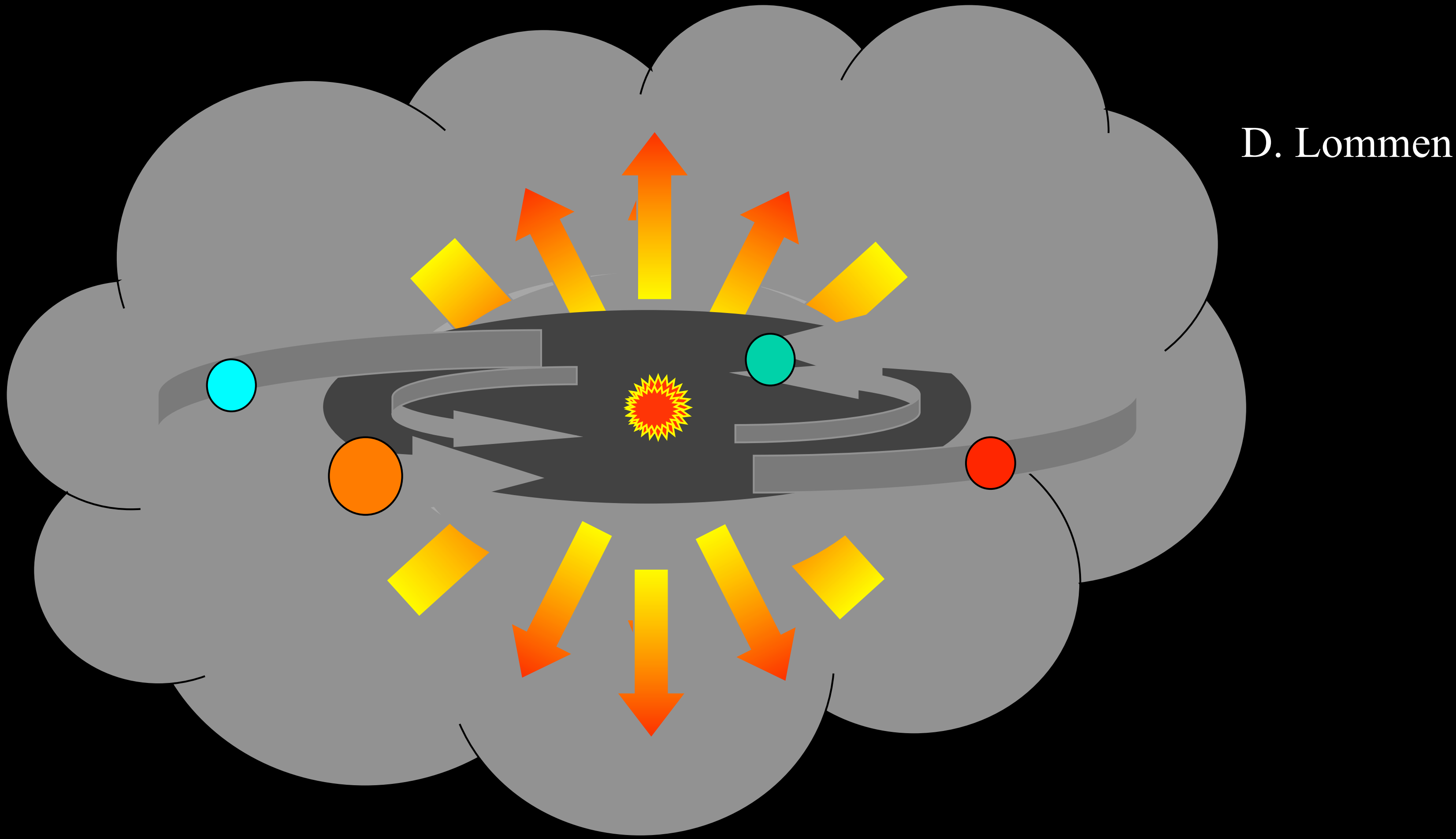
- Water
  - Building on ISO, SWAS, Odin heritage
- Cooling lines: high-*J* CO, OH, [O I], [C II]
- Simple hydrides: OH^+, H_2O^+, …
- Complex organic molecules
  - Lots of lines with very good relative calibration

Water In Star-forming regions with Herschel
The WISH team

Leiden April 28 2010: 70+ scientists from 30 institutions (PI: EvD)
15 papers in Herschel A&A first results issues

Summary in van Dishoeck et al., to be subm to PASP

Follow molecules during star and planet formation

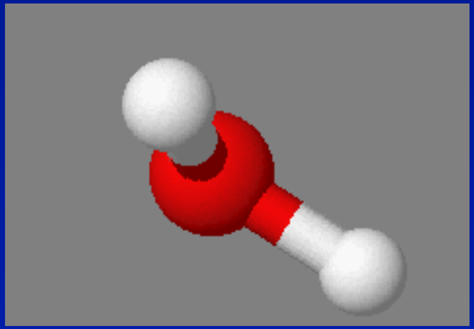


Dark pre-stellar cores → Low-mass YSOs → Disks
Infrared dark clouds Intermediate mass YSOs
High-mass YSOs

Why water?

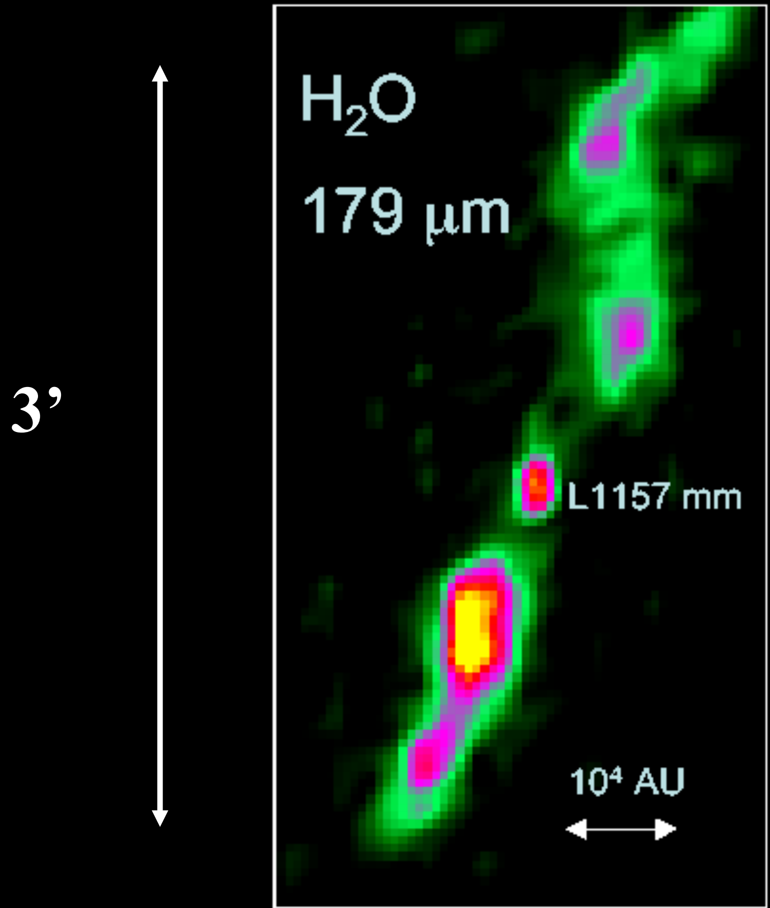
- Unique probe of different physical regimes and processes → natural filter of warm gas
  - H_2O abundance shows large variations: $<10^{-8}$ (cold) – $3.\ 10^{-4}$ (warm)
  - Complementary to CO
- Main reservoir of oxygen → affects chemistry of all other species
  - Traces basic processes of freeze-out onto grains and evaporation, which characterize different stages of evolution
- Astrobiology: water associated with life on Earth → characterize water 'trail' from clouds to planets, including origin of water on Earth

pre-stellar cores → YSO's → disks → comets



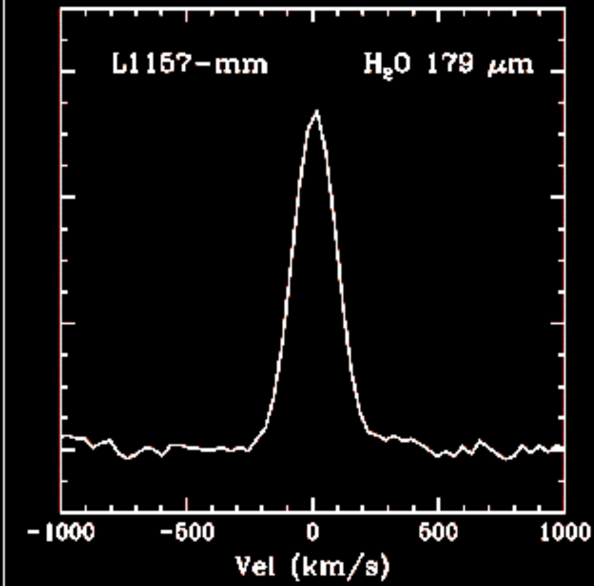
Early highlight

Herschel-PACS image of water in proto-stellar systems



L1157-mm outflow

D = 440 pc, L_{bol} = 11 L_o



Nisini, Liseau, Tafalla, Benedettini + WISH team

Water traces ‘hot spots’ where shocks dump energy into cloud

Why water?

- **Unique probe of different physical regimes and processes → natural filter of warm gas**
  - **H_2O abundance shows large variations: $<10^{-8}$ (cold) – 3. 10^{-4} (warm)**
- **Main reservoir of oxygen → affects chemistry of all other species**
  - **Traces basic processes of freeze-out onto grains and evaporation, which characterize different stages of evolution**
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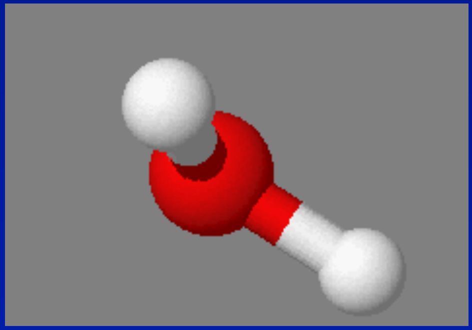
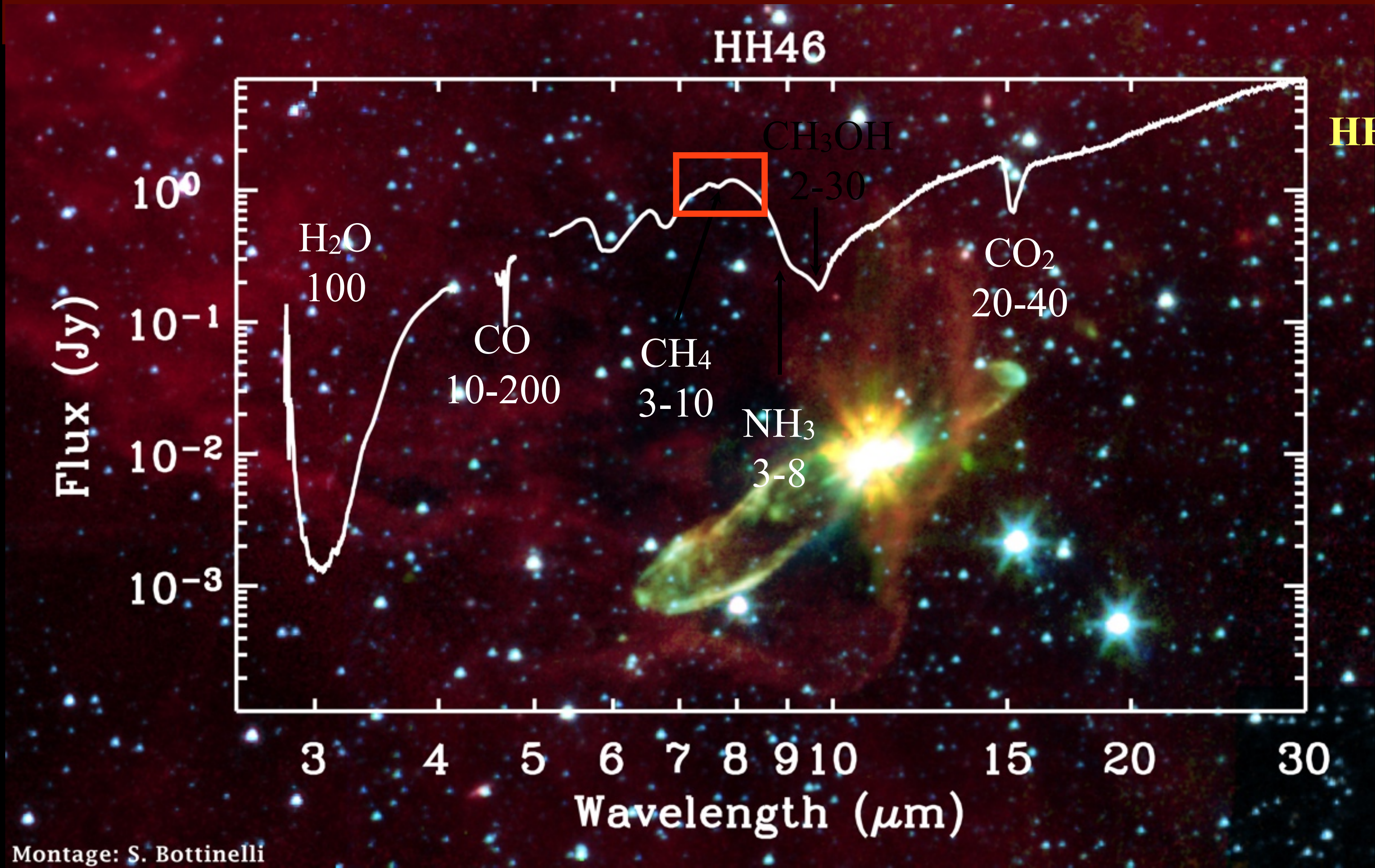
pre-stellar cores → YSO's → disks → comets



www.strw.leidenuniv.nl/WISH

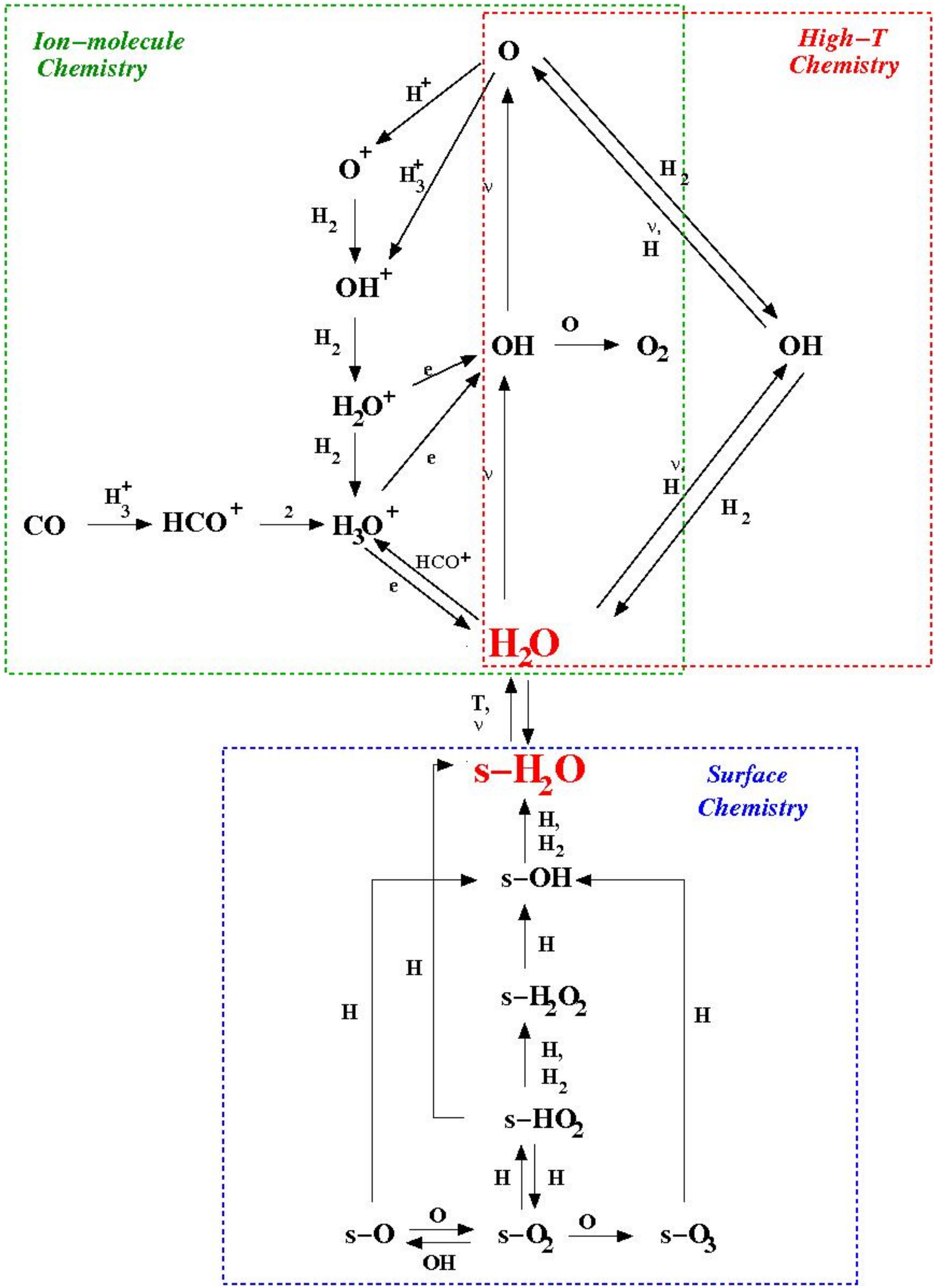
Ices are abundant and common!



- Ices can contain significant fraction of heavy elements (50% or more)

Boogert, Pontoppidan et al. 2008

Three routes to water



Surface scheme based on Ioppolo et al. 2010, Cuppen et al. 2010

H_2O chemistry

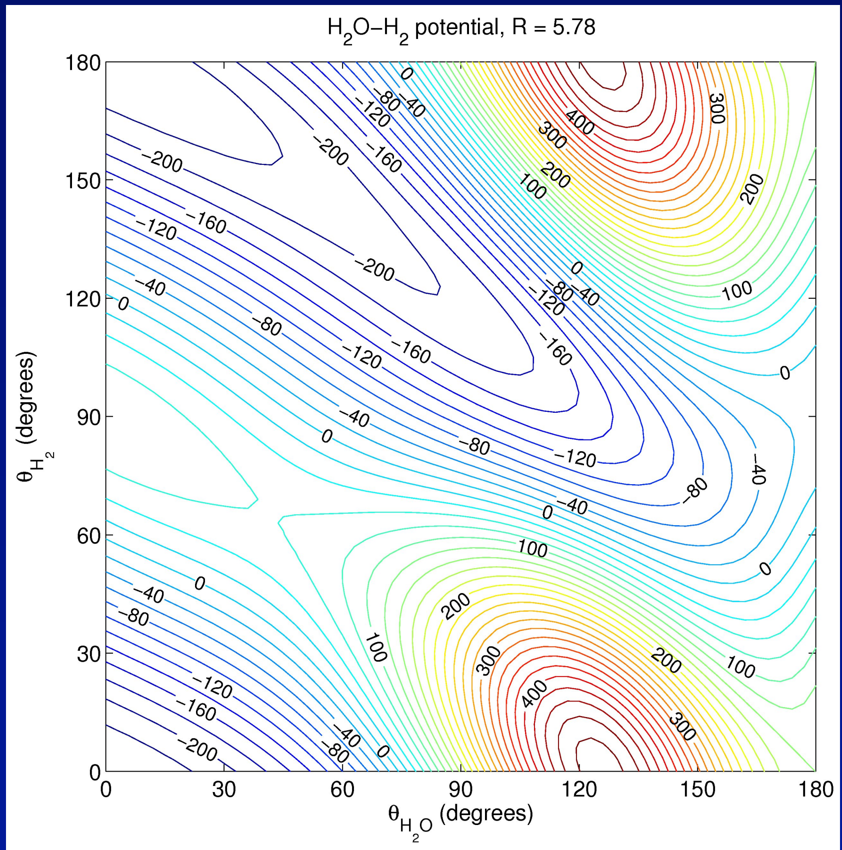
- Ion-molecule chemistry (low T):
  - $O + H_3^+ \rightarrow OH^+ \xrightarrow{H_2} H_2O^+ \rightarrow H_3O^+ \xrightarrow{e} H_2O$

    Typical H_2O abundances ~10^{-7}
- High-temperature chemistry (>230 K):
  - $O \xrightarrow{H_2} OH \rightarrow H_2O$

    Drives all gas-phase O into $H_2O \Rightarrow$ abundance $>10^{-4}$
- Photodissociation by UV radiation:
  - $H_2O \rightarrow OH + H$
- Ice evaporation (>100 K): $10^{-5} - 10^{-4}$
- Freeze-out (<100 K): $<10^{-7}$

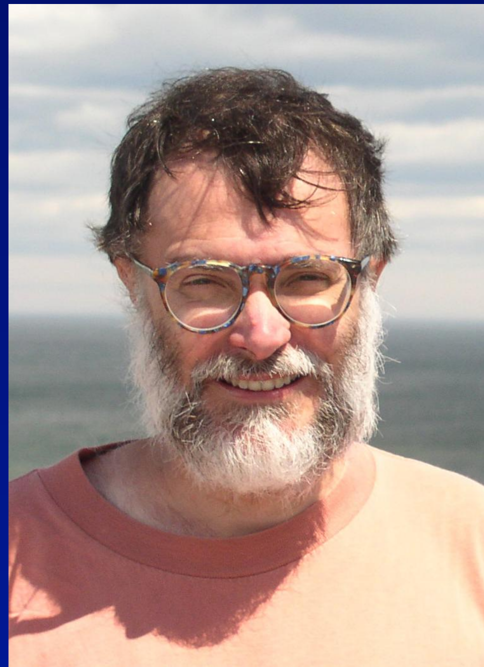
Collisional rate coefficients $H_2O - H_2$

9D potential surface



Valiron, Wiesenfeld et al. 2008
Figure by van der Avoird

Thanks Pierre!

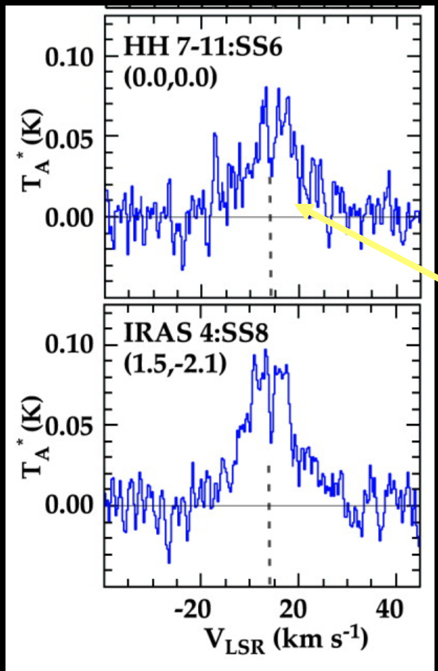


Accurate molecular data needed! **Abundances $\propto \sigma$**

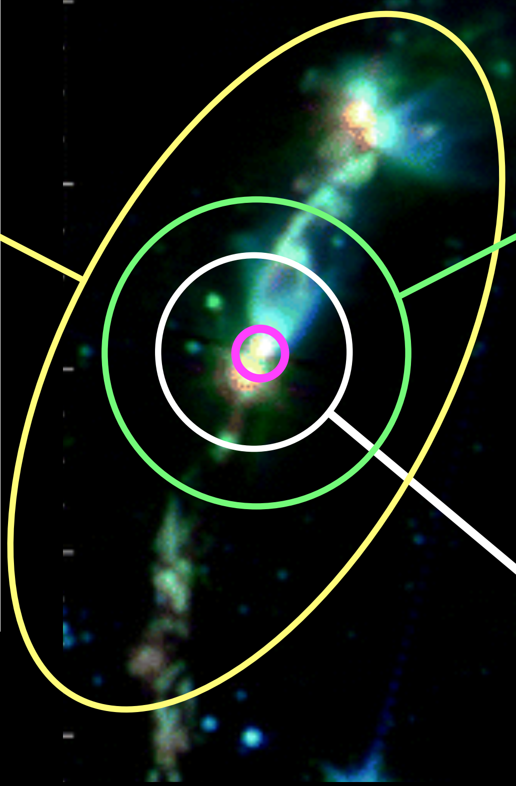
Previous observations of H_2O

SWAS H_2O $1_{1,0}$-$1_{0,1}$

Ø = 3.3'x4.5'

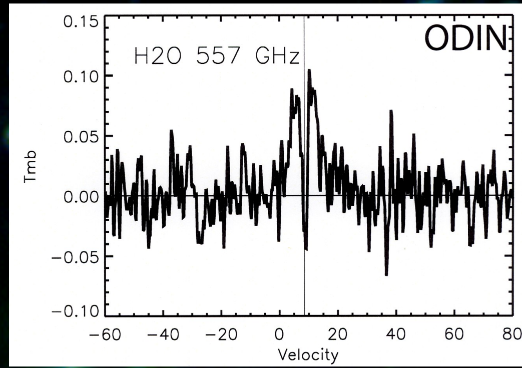


(Bergin et al. 2004)



ODIN H_2O $1_{1,0}$-$1_{0,1}$

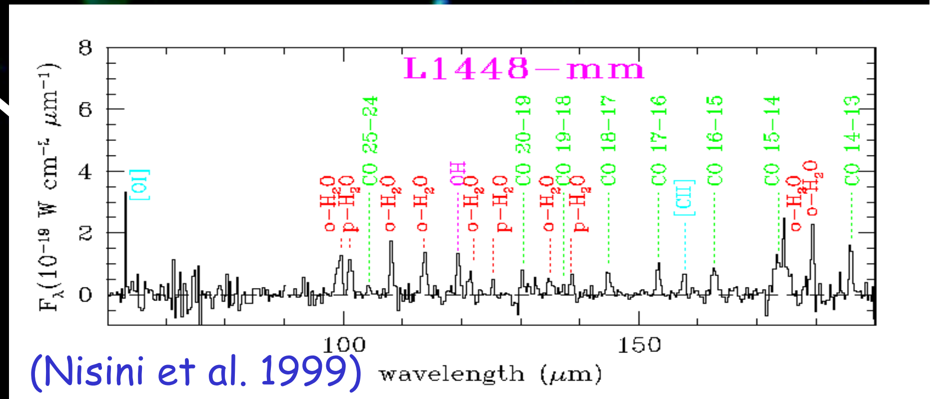
Ø = 126"



(Olberg et al. 2006)

ISO-LWS 55-180 μm Ø = 80"

ISO-SWS 2.5-45 μm

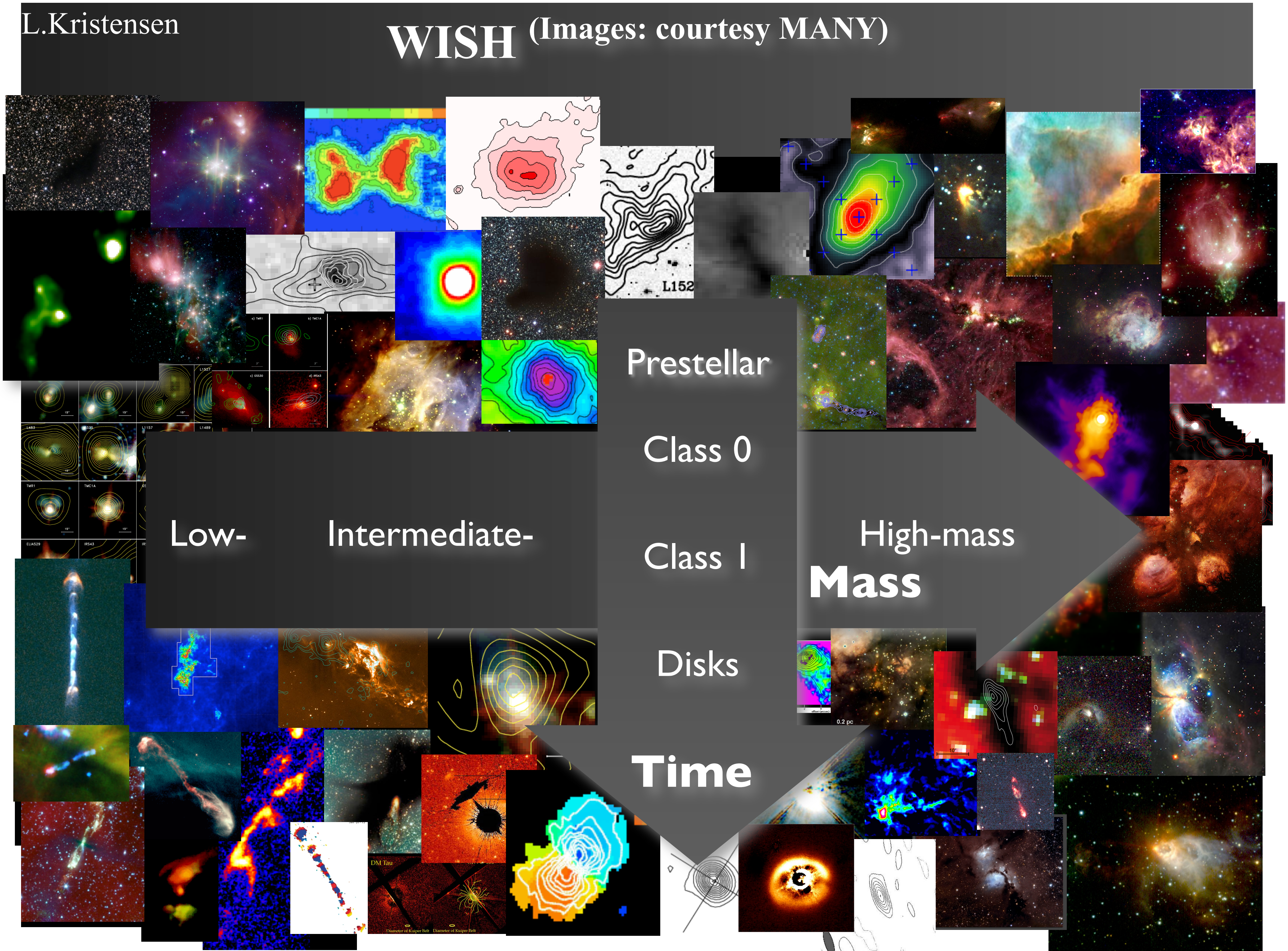


(Nisini et al. 1999)

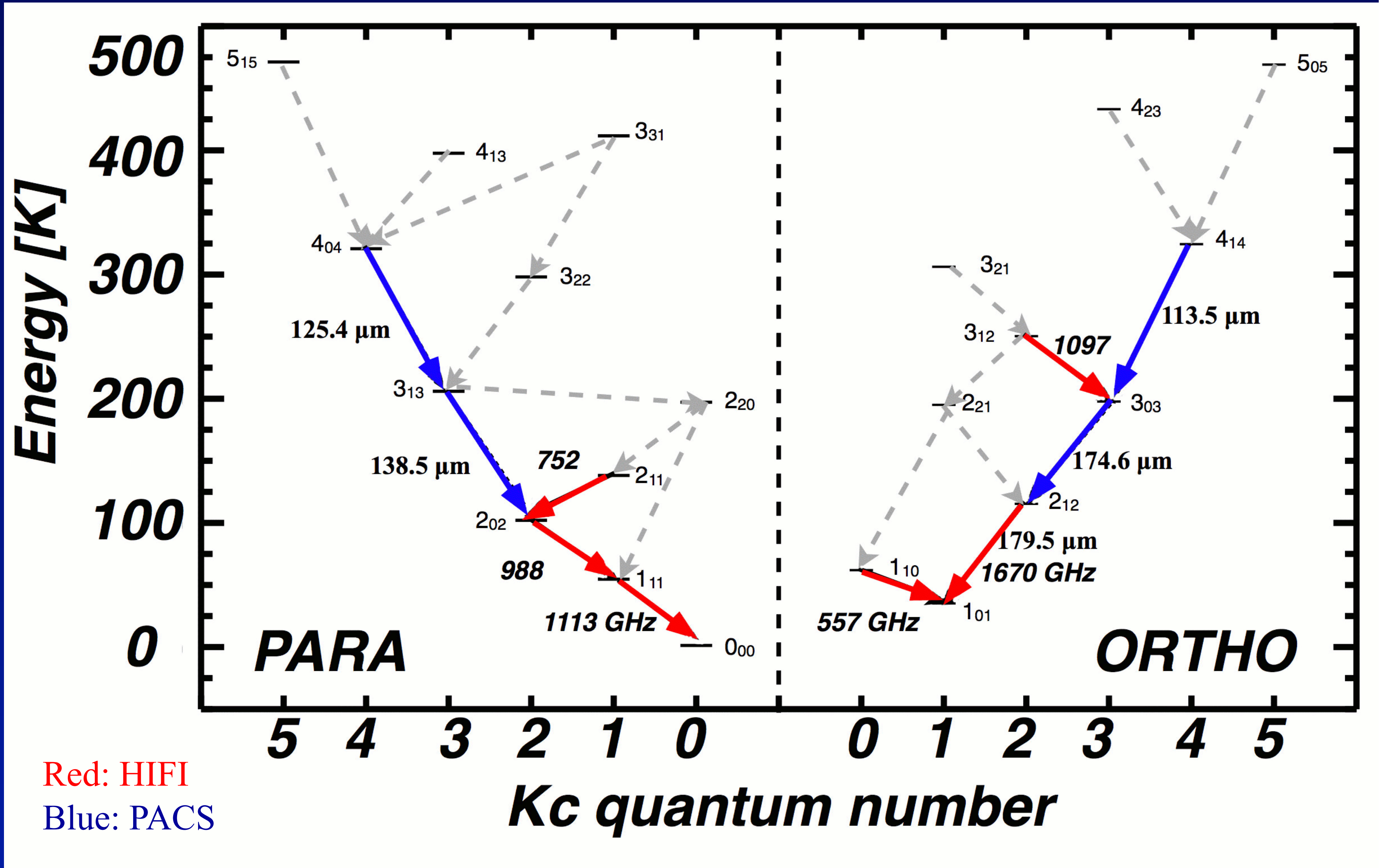
(Boonman et al. 2003)

Herschel Ø = 9.4" - 40"

⇒ ***provides orders of magnitude increase in spatial and/or spectral resolution and sensitivity***

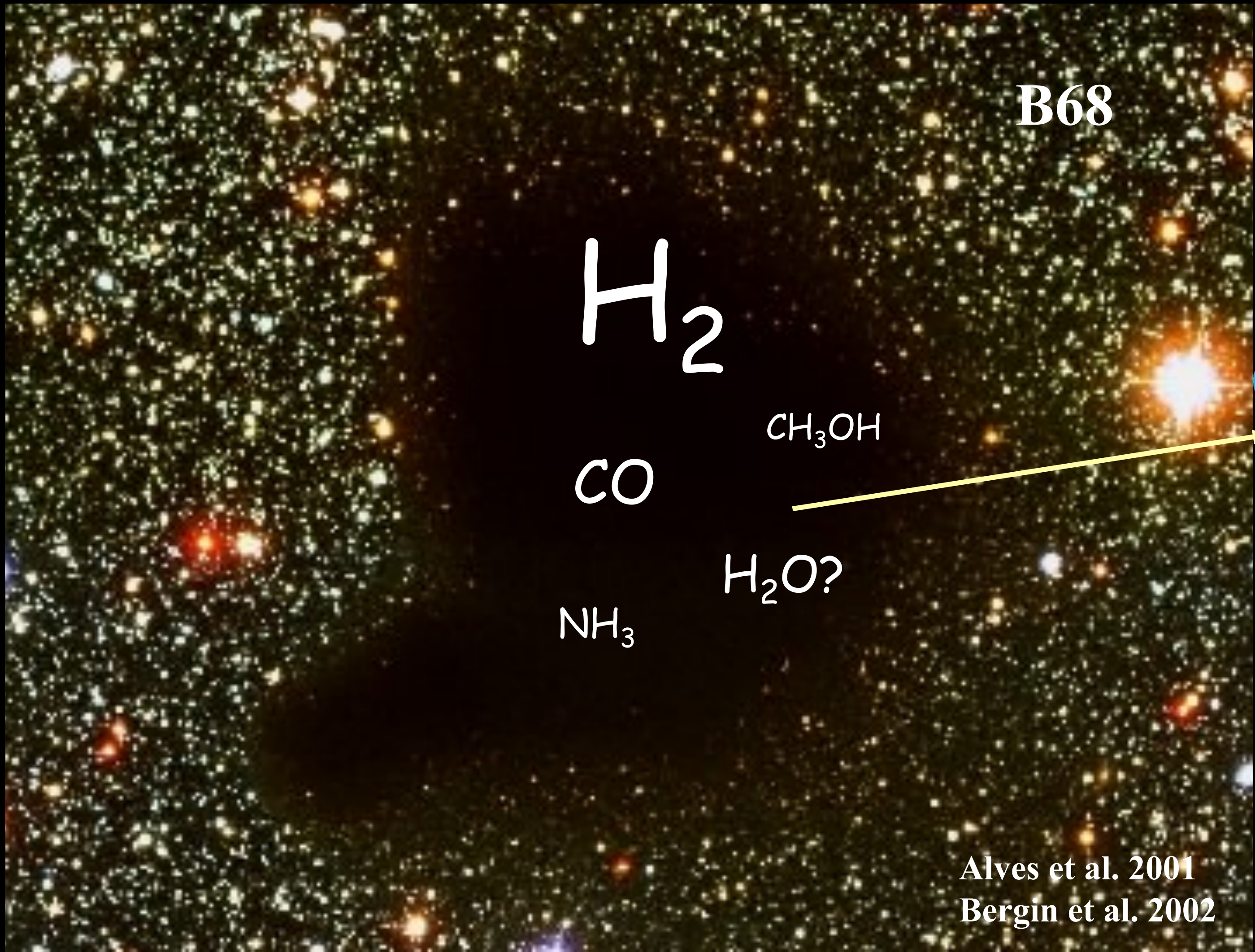

L.Kristensen
WISH (Images: courtesy MANY)
Prestellar
Class 0
Class I
Disks
Time
Low-
Intermediate-
High-mass
Mass

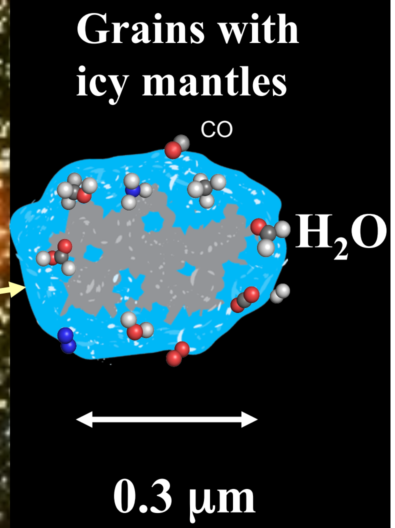
H_2O lines: HIFI vs PACS



Observe mix of low- and high-excitation lines to probe cold and hot environments

Pre-stellar cores



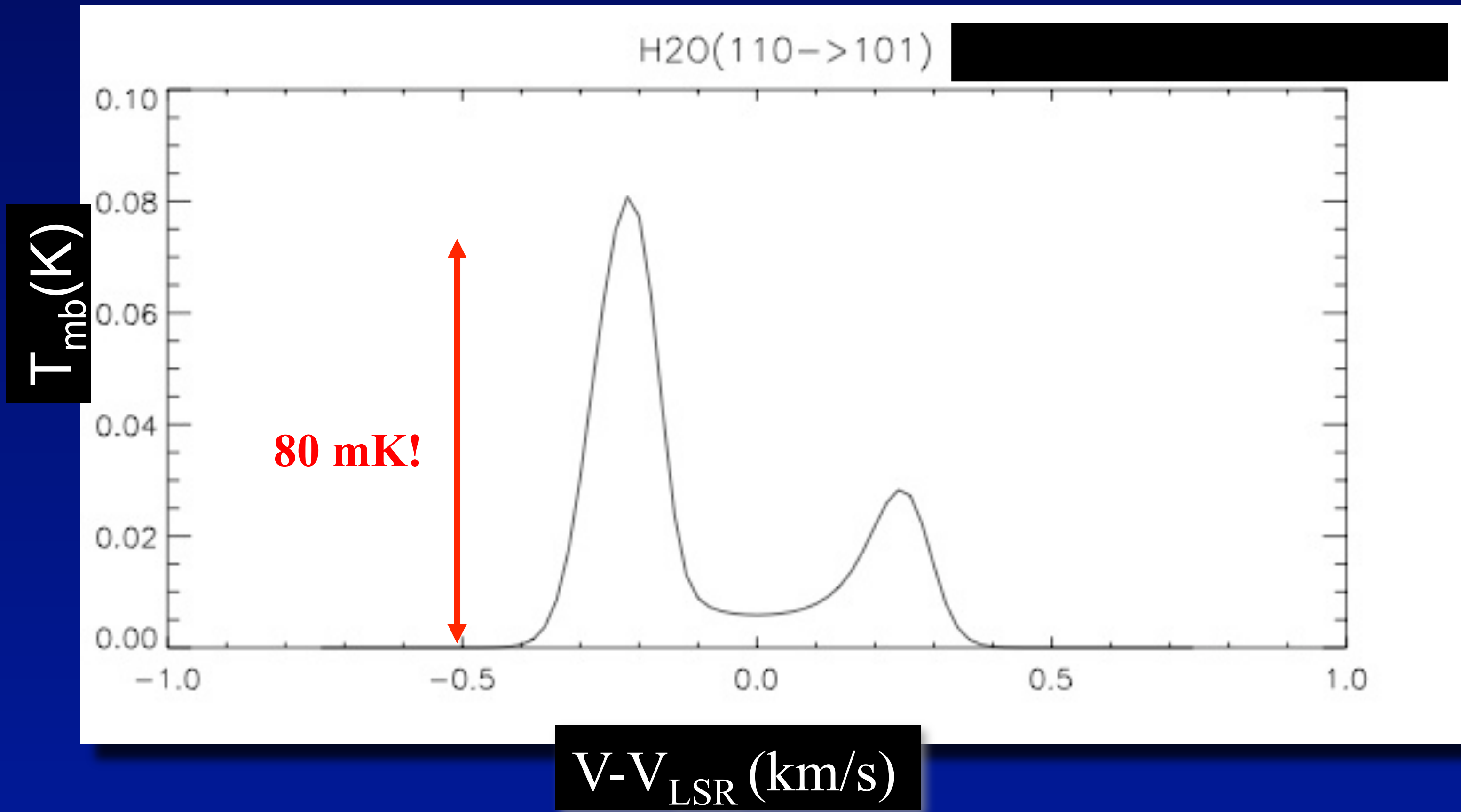


t_{depl}~$2.10^9/n$ yr

n=2.10^4 – 5.10^5 cm^{-3}, T=10 K

Many molecules frozen out onto grains; gas?

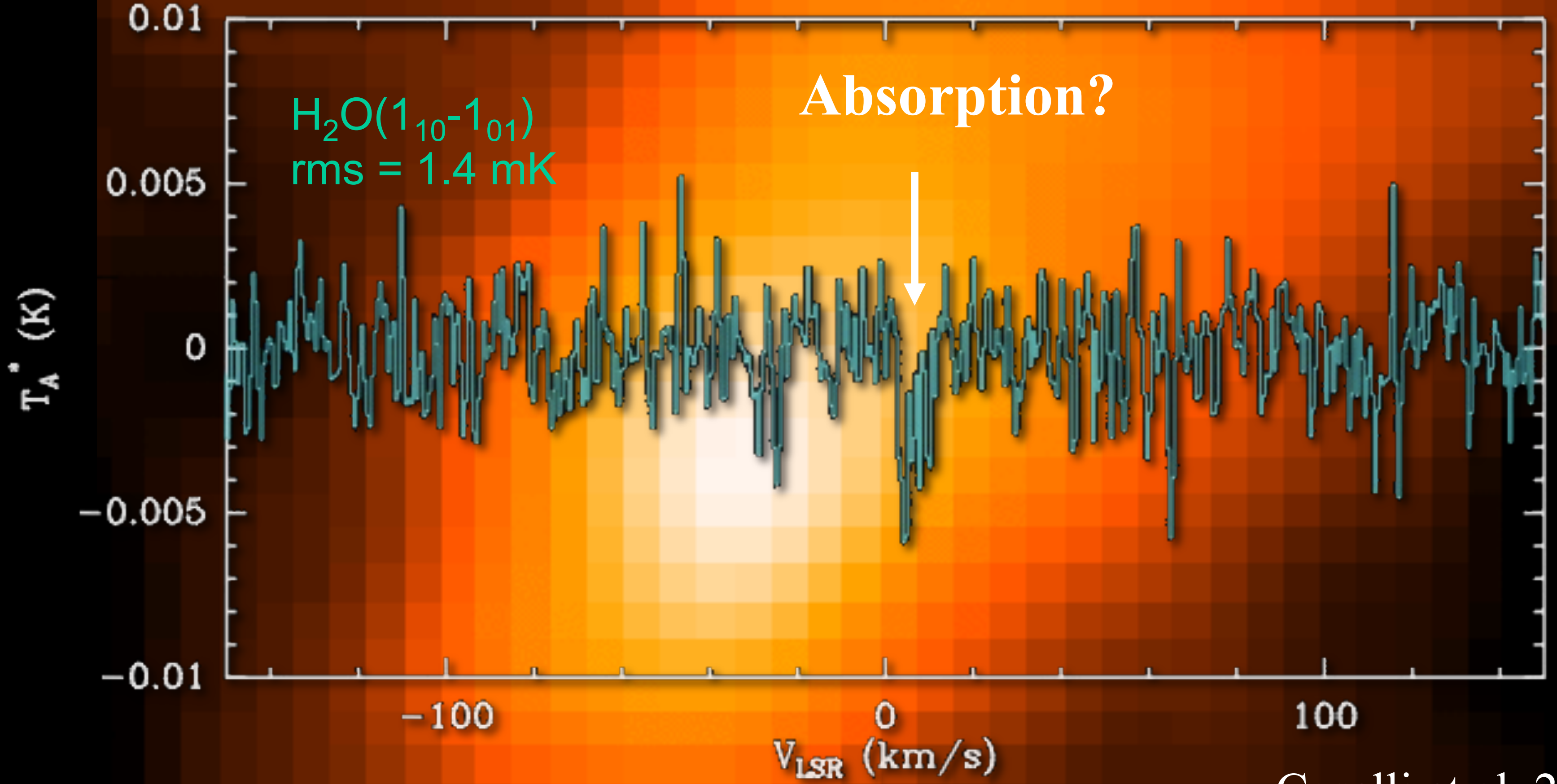
Pre-Herschel model prediction



Caselli, Aikawa,
Keto et al. in prep

The prestellar core L1544

Pushing the limits of HIFI



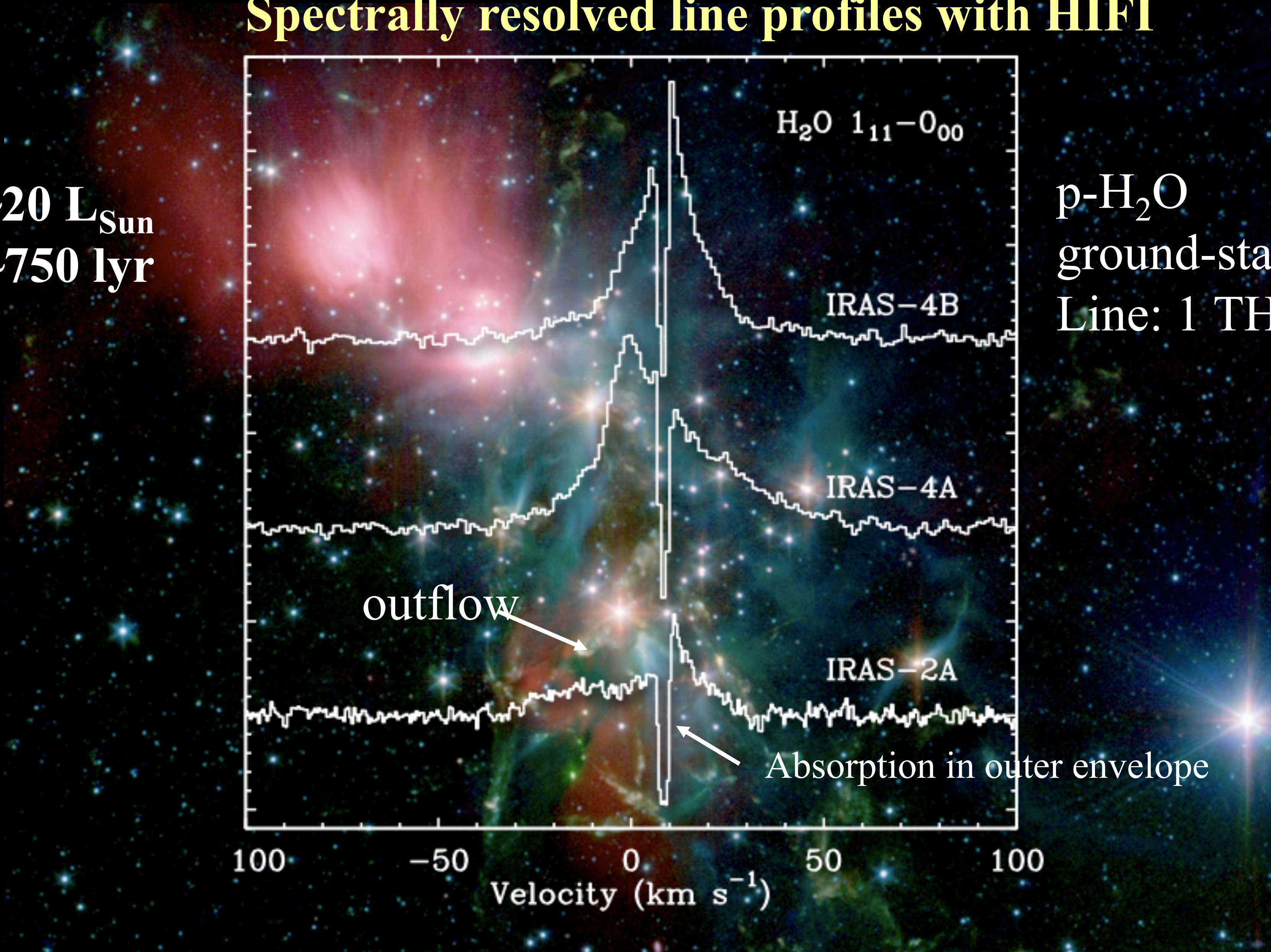
Caselli et al. 2010

Lines up to factor 100 weaker than predicted
⇒ Most water frozen out except for thin layer

Low-mass protostars: NGC 1333

Spectrally resolved line profiles with HIFI

L~20 L_{Sun}
D~750 lyr

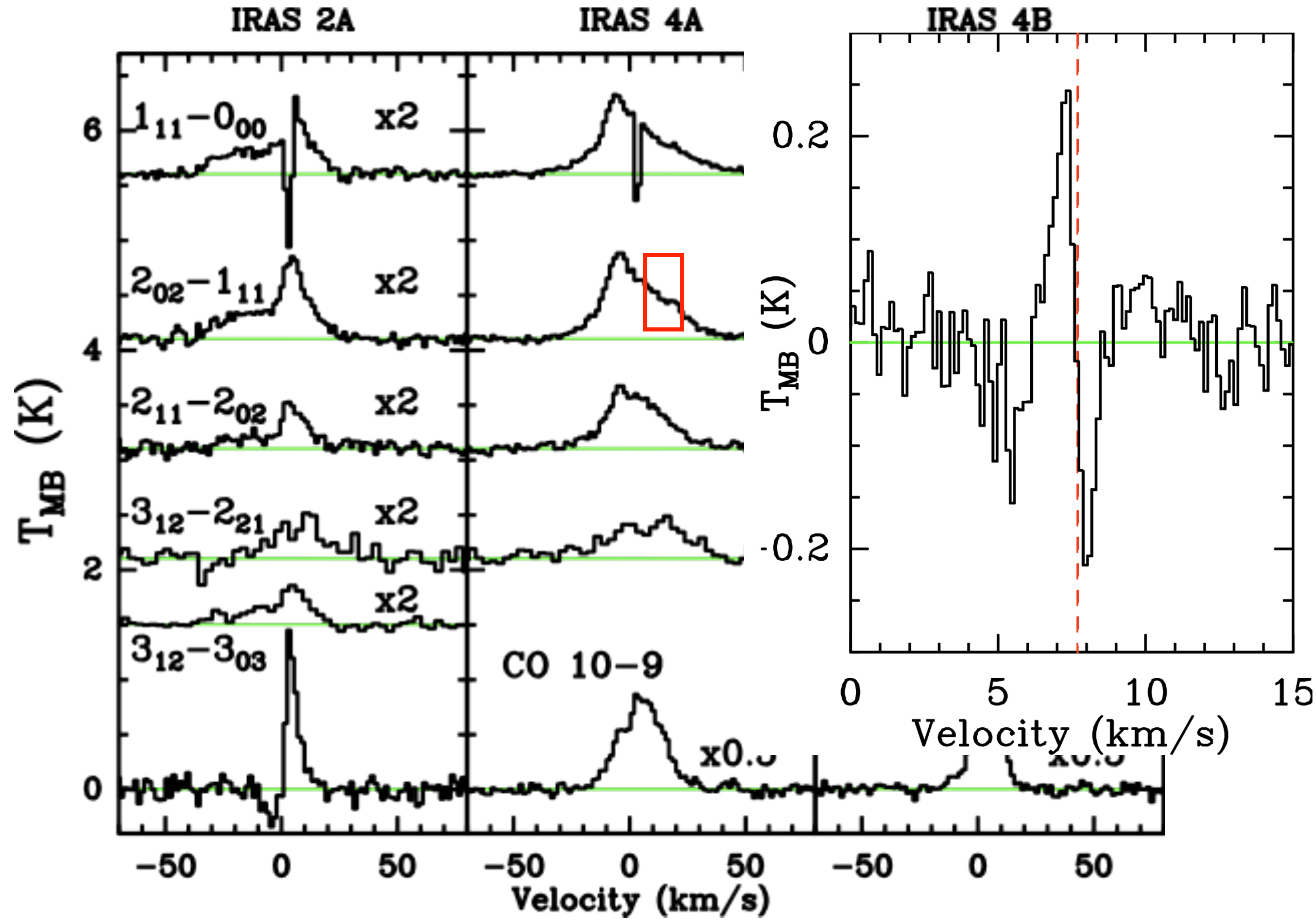


p-H_2O
ground-state
Line: 1 THz

Broad: outflow dominates

Kristensen, Visser et al. 2010

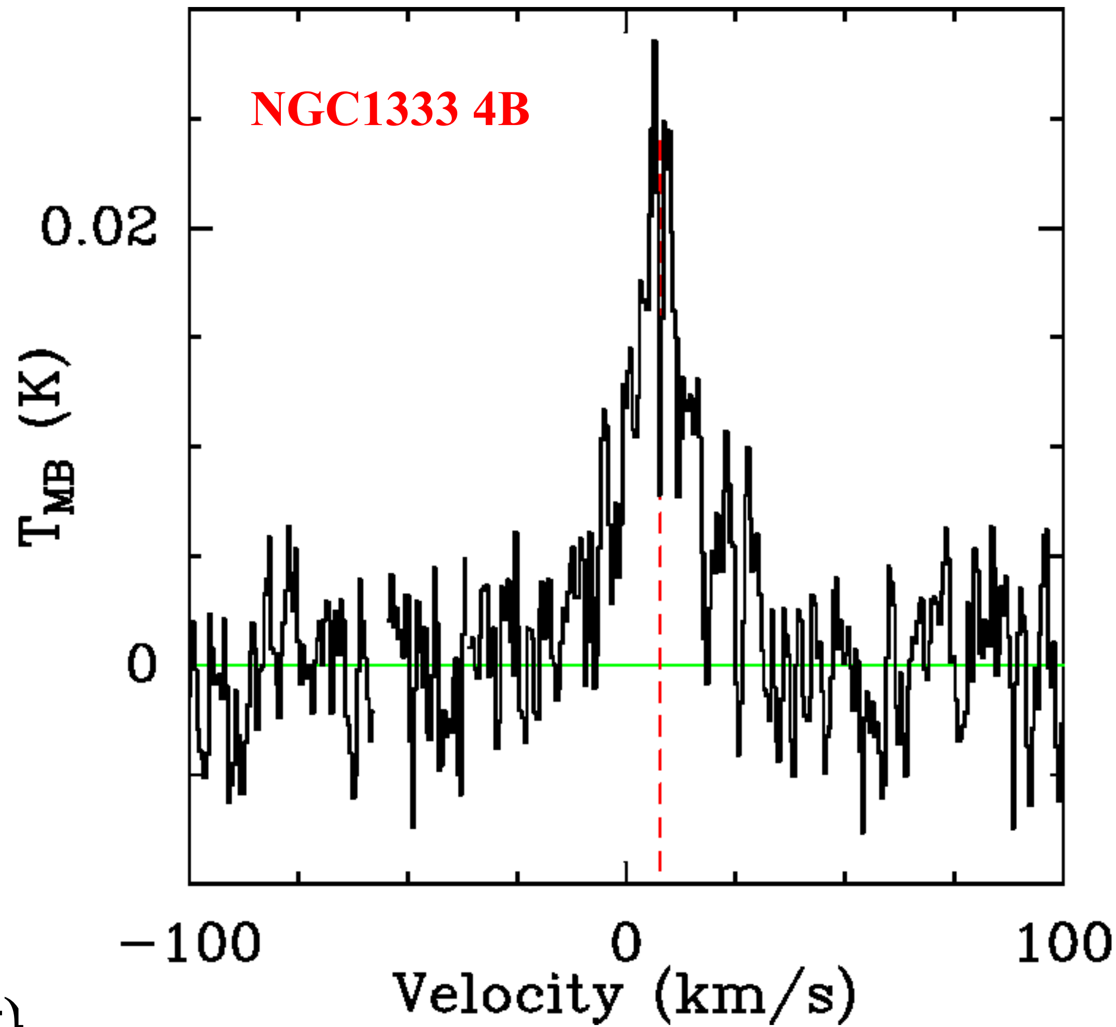
Excited H_2O and CO lines



Kristensen, Yildiz, Visser et al.

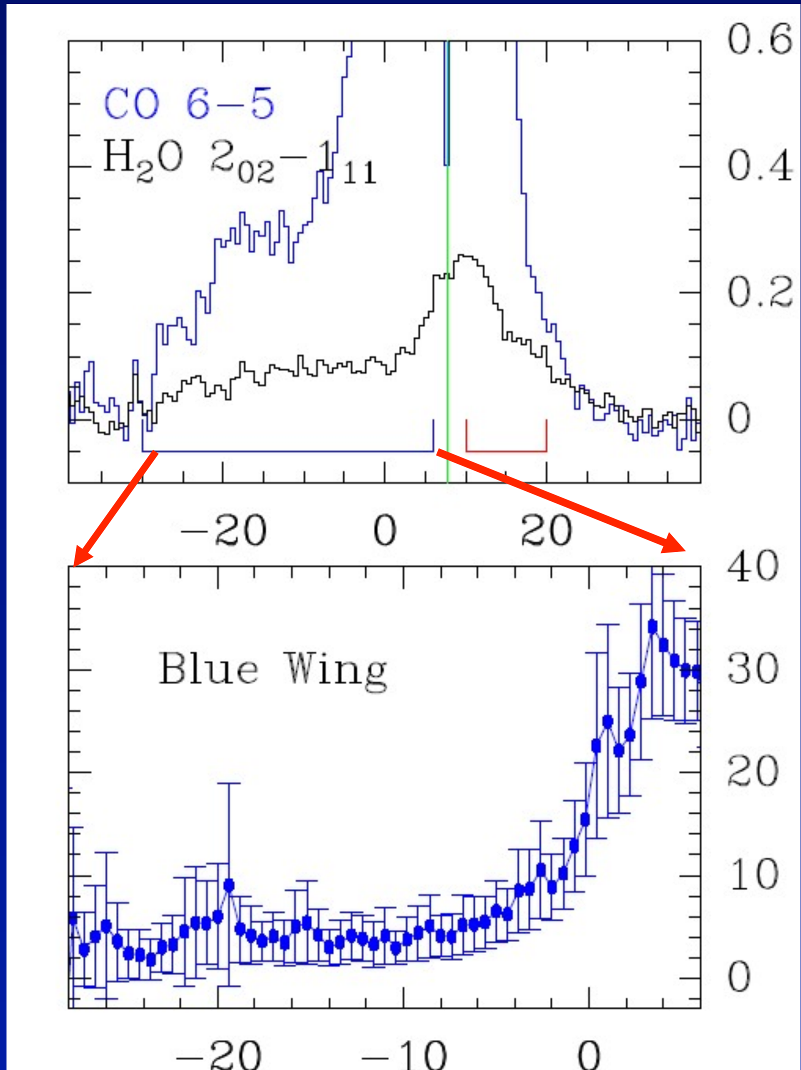
Surprise:broad and weak $H_2{}^{18}O$ lines

Absence of *narrow* $H_2{}^{18}O$ lines, also for higher J, limit water abundance in inner envelope



Abundance H_2O:
high in outflow (10^{-5}-10^{-4})
but low in outer envelope (~10^{-8})
Inner envelope (<10^{-5})

H_2O/CO abundance increases with velocity



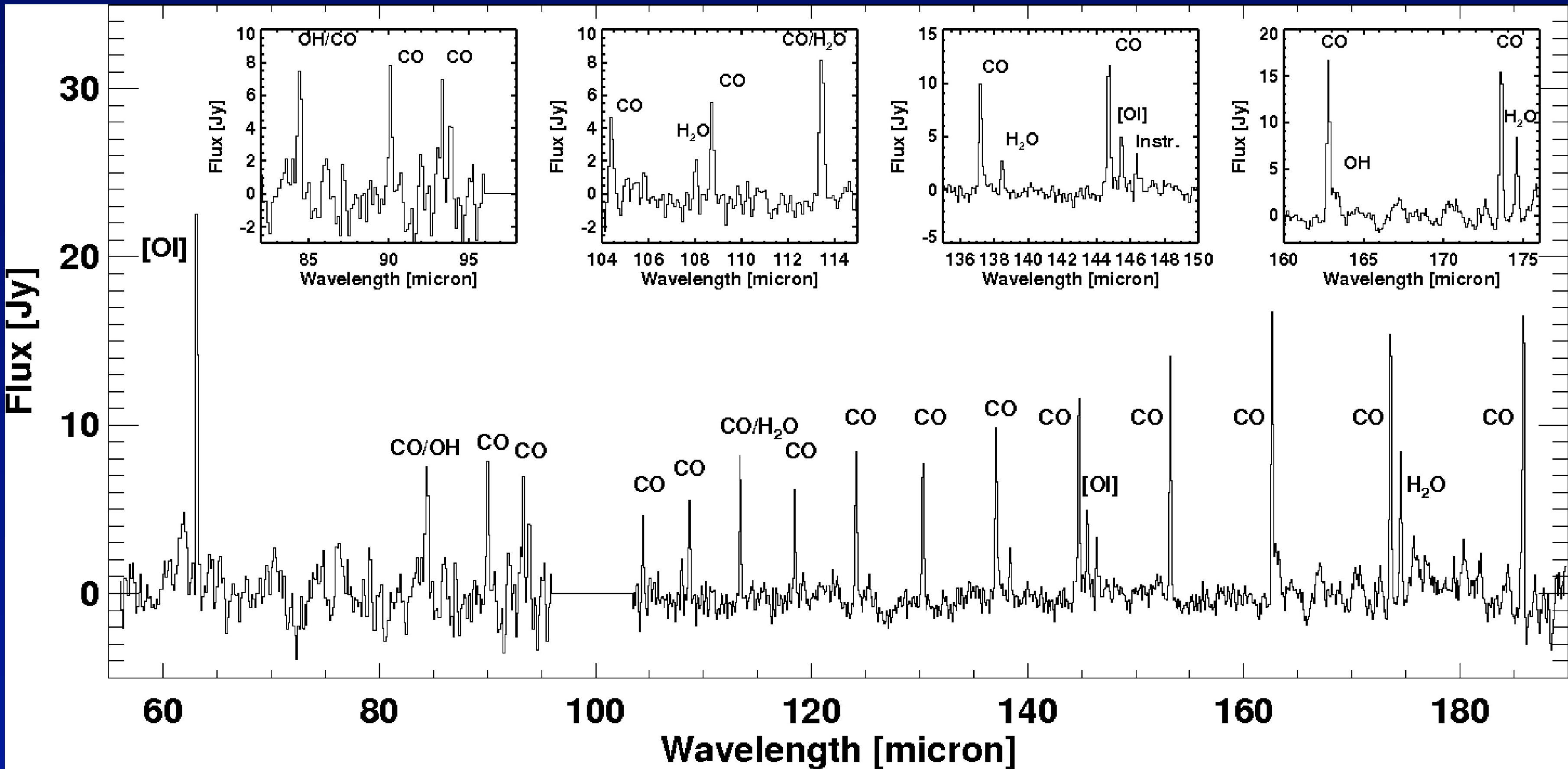
Note high quality data!

CO/H_2O
Intensity ratio

See also
LeFloch et al. 2010
Codella et al. 2010

Kristensen et al. 2010

H_2O and CO with PACS

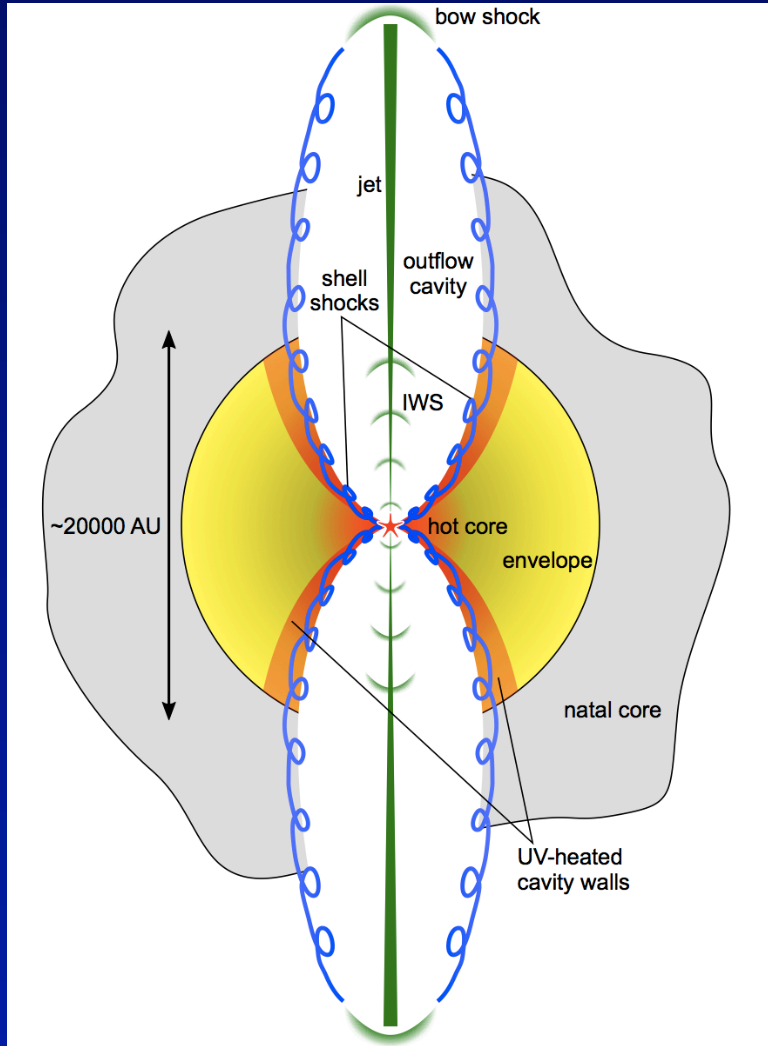


Full PACS spectral scan: complete CO ladder

Van Kempen + DIGIT team 2010

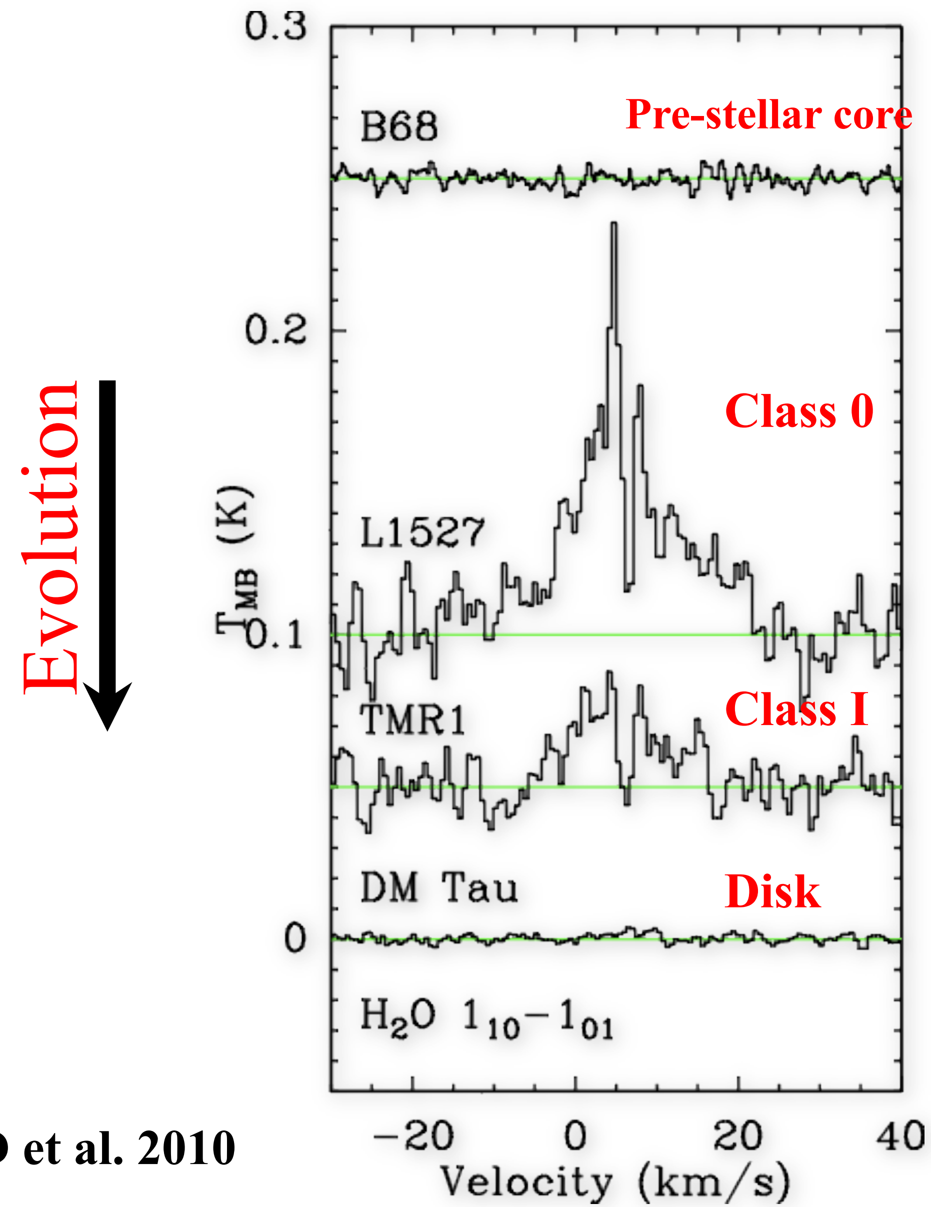
Origin of water and hot CO in low-mass protostars

- Hot core?
- Outflows?
- UV heated cavity walls?



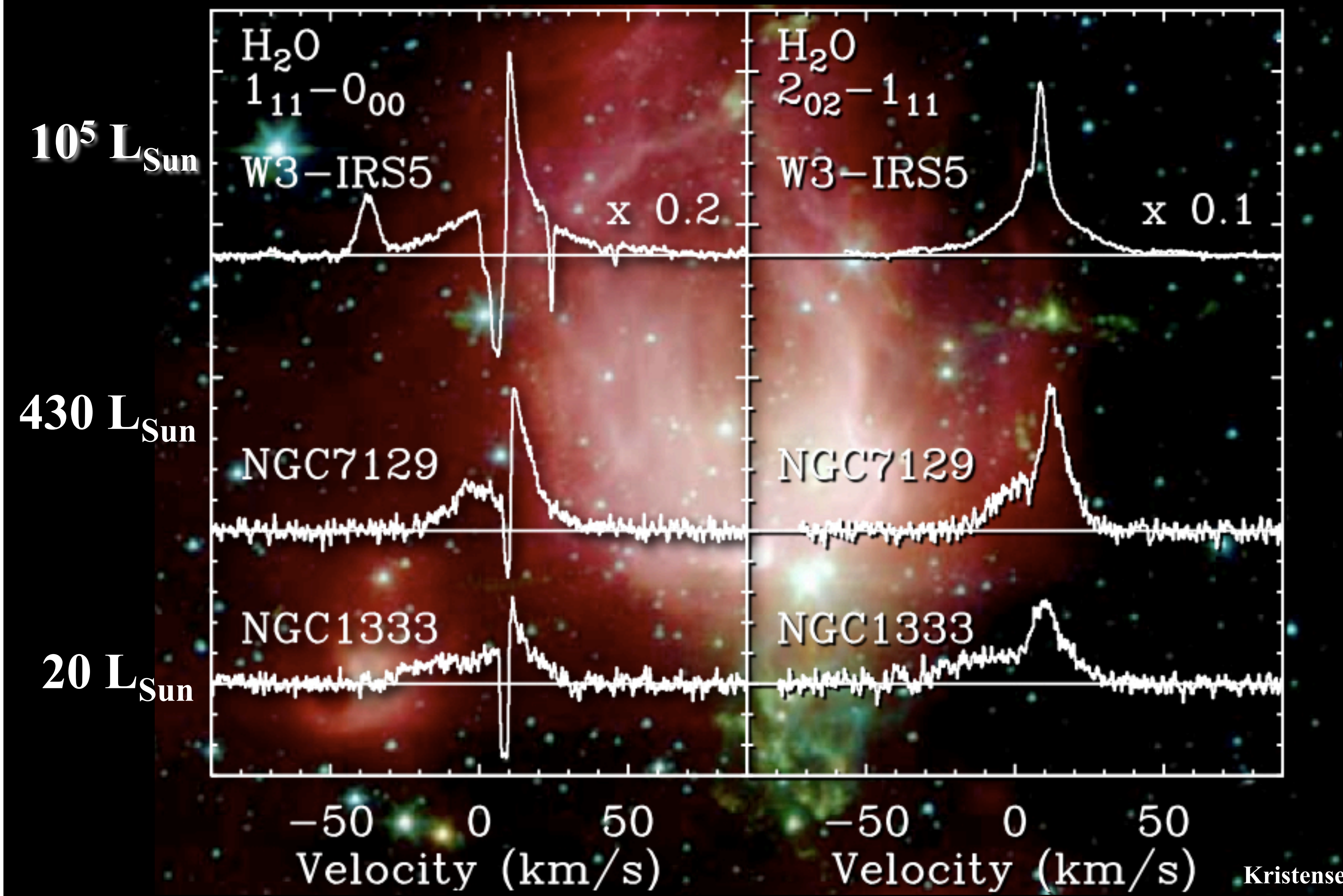
H_2O 557 GHz profile evolution low mass

Note weaker H_2O emission in Stage 1 sources



vD et al. 2010

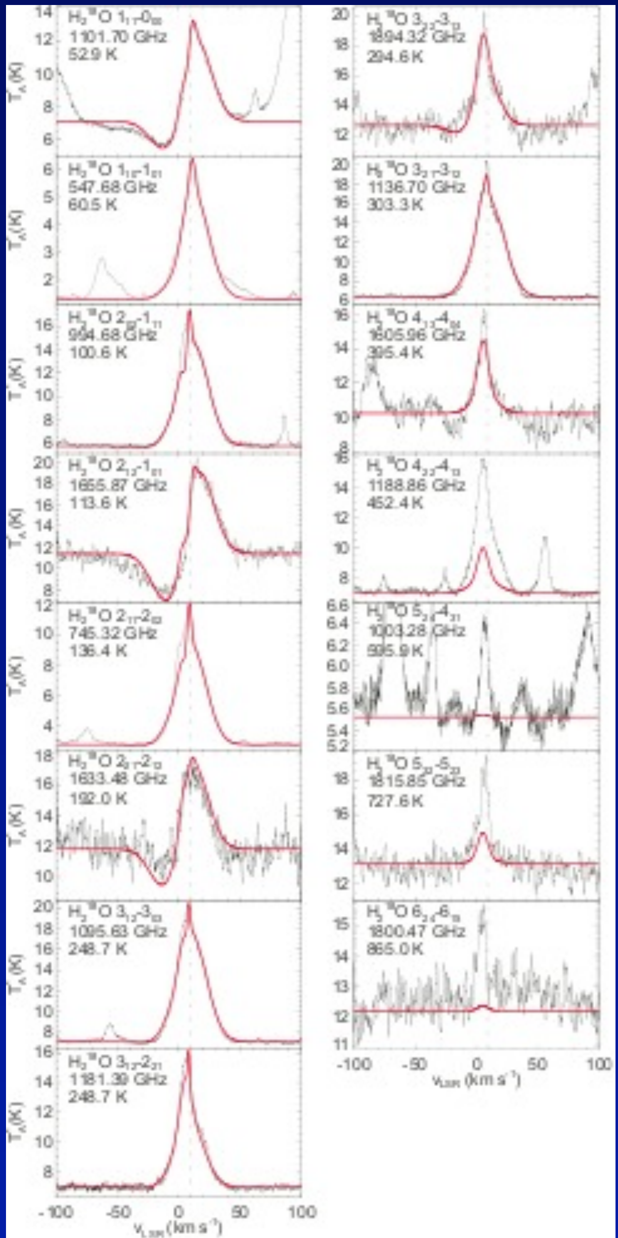
From low to high mass protostars



Kristensen et al. 2010
Johnstone et al. 2010
Chavarria et al. 2010

Note similar profiles

Water in massive protostars



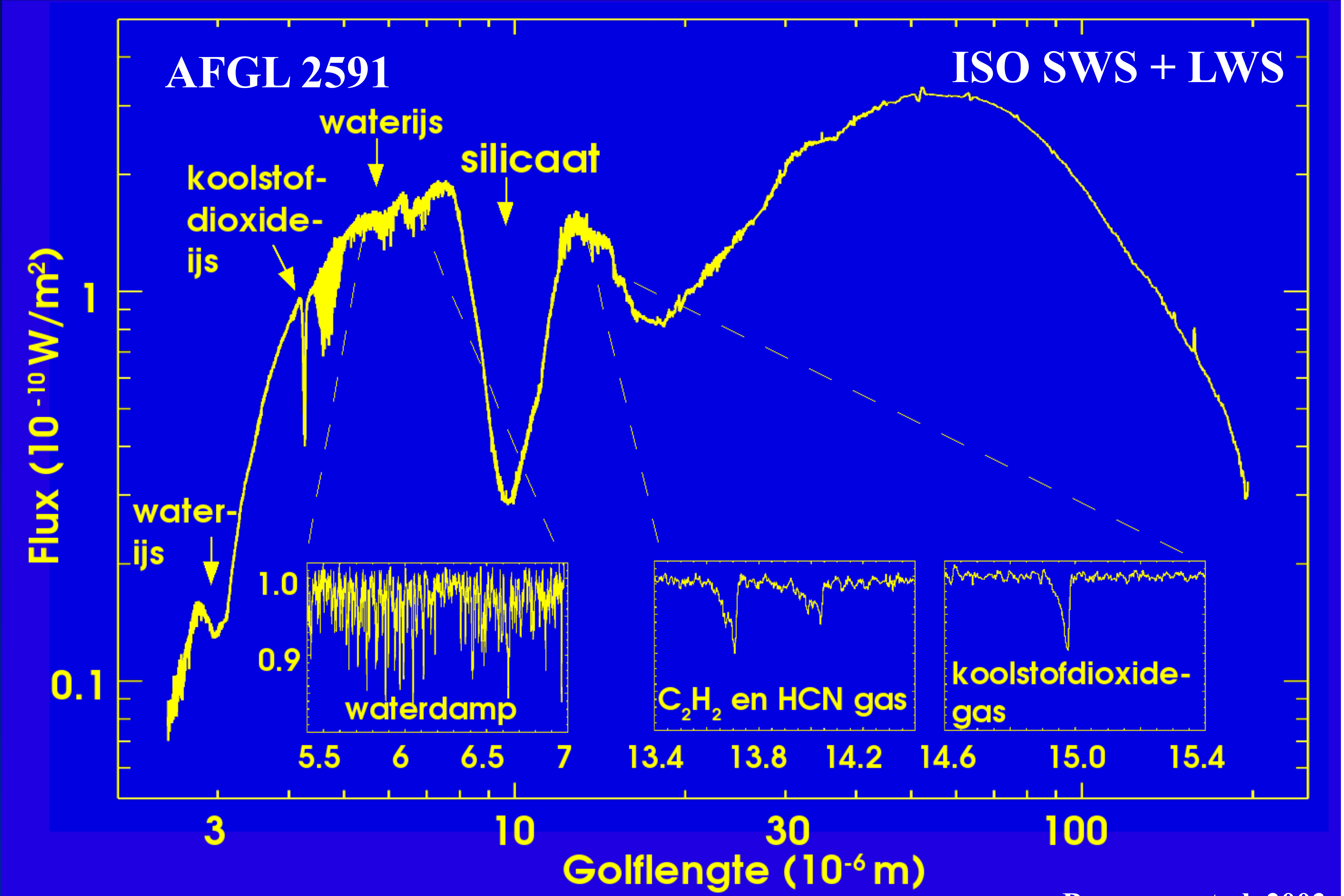
- DR 21 (OH): p-H_2O 1_{11}-0_{00} line
  - Foreground clouds, outer envelope, outflow
  - Van der Tak et al. 2010
- Orion: analysis of 15 $H_2{}^{18}O$ lines ⇒ H_2O/H_2 = (1-7)x 10^{-5}
  - Melnick et al. 2010
- NGC 6334 I: analysis of 12 H_2O, $H_2{}^{18}O$ and $H_2{}^{17}O$ lines
  - Foreground clouds: 10^{-8}
  - Hot core: ~2x10^{-6} (uncertain)
  - Outflow: 4x10^{-5}
  - Emprechtinger et al. 2010

Also: Chavarria et al. 2010, Marseille et al. 2010

Water results protostars

- Gaseous water abundance in cold regions is very low: 10^{-8} or lower
  - Lower than thought before (unless 'dark')
  - Water (vapor) is *not* everywhere!
- Warm H_2O emission is dominated by shocks + UV photon heated component along outflow walls: $\sim10^{-5}$
  - Hot cores so far only seen for a few massive YSOs: $<10^{-4}$
- Herschel CO and H_2O lines require models beyond spherical symmetry

Probing hot water with infrared absorption



Boonman et al. 2003

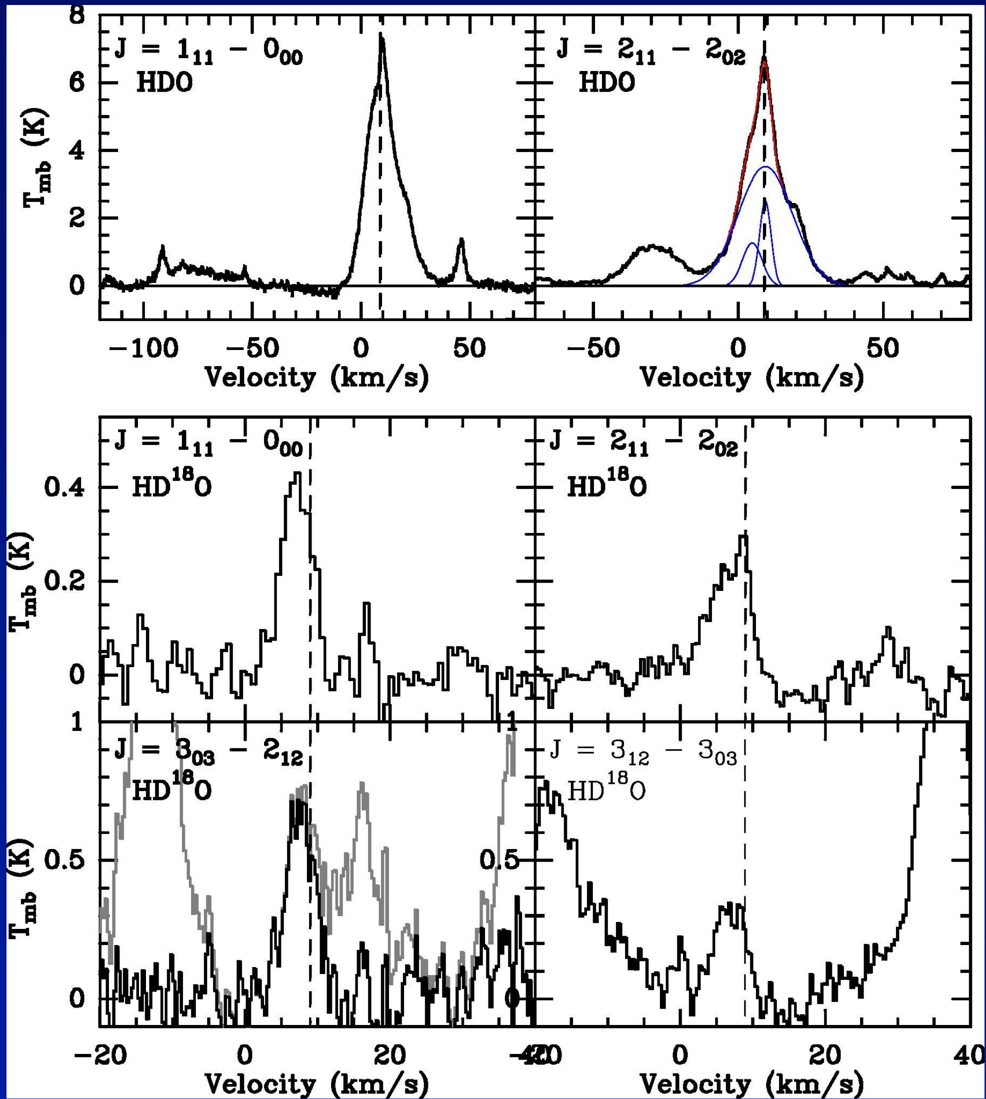
Puzzling HDO/H_2O ratios

- High-mass hot cores: 0.01 vs. 0.001?
- Low mass protostars:
  - IRAS 16293 -2422: 0.03
    - Parise et al. 2005
  - NGC 1333 IRAS2A: 0.01
    - Liu et al. 2010
  - NGC 1333 IRAS4B: <0.0006
    - Jørgensen et al. 2010

Problem is determining H_2O rather than HDO

see also Comito et al. 2010 for SgrB2(M)

Detection $HD^{18}O$ in Orion



Use $HD^{18}O$ to better constrain HDO in Orion

⇒$HDO/H_2O = 0.01$

Consistent with Persson et al. 2007, but higher than previous estimates

Bergin et al. 2010

Puzzling HDO/H_2O ratios

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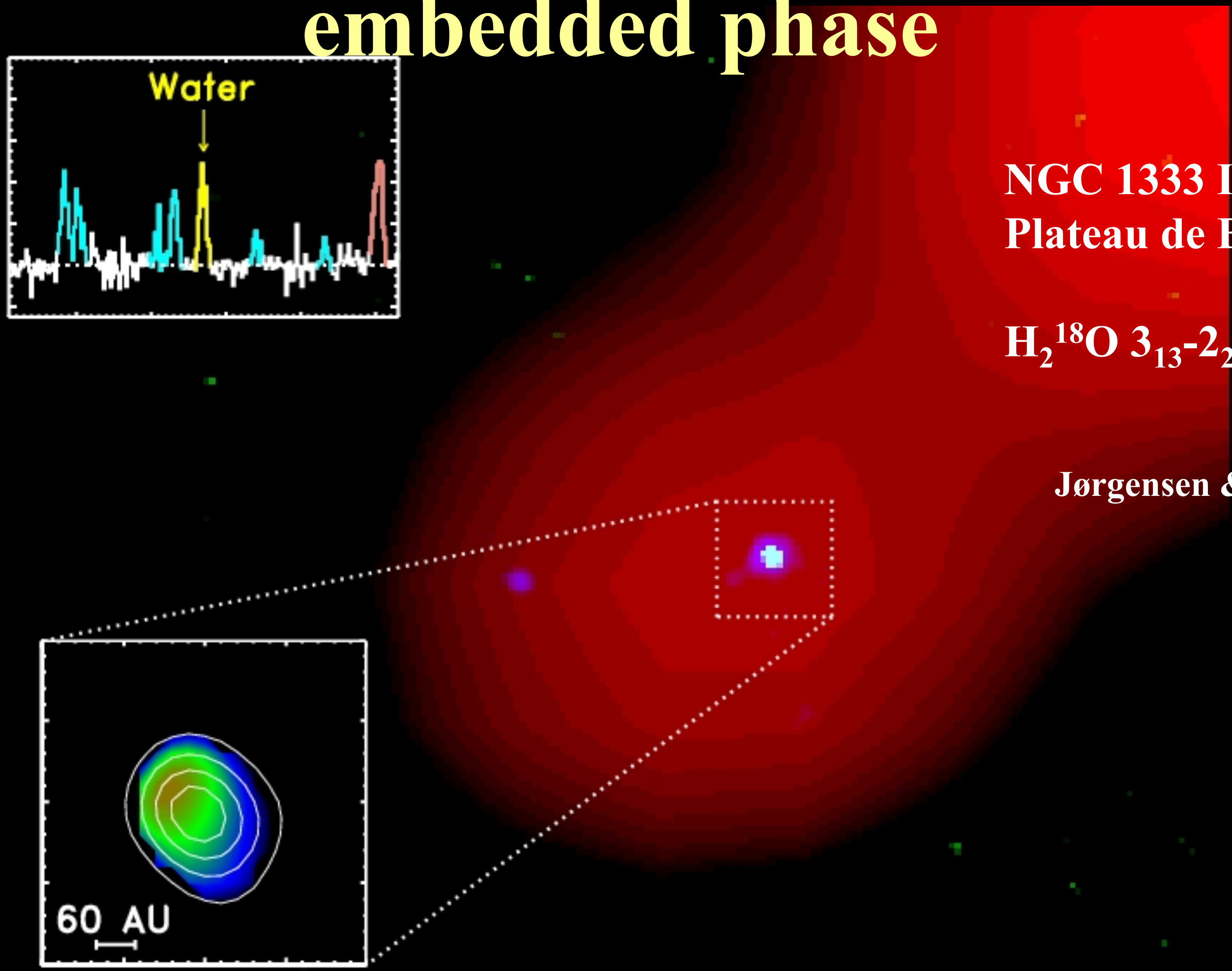
see also Comito et al. 2010 for SgrB2(M)

Hot water in a disk in the deeply embedded phase



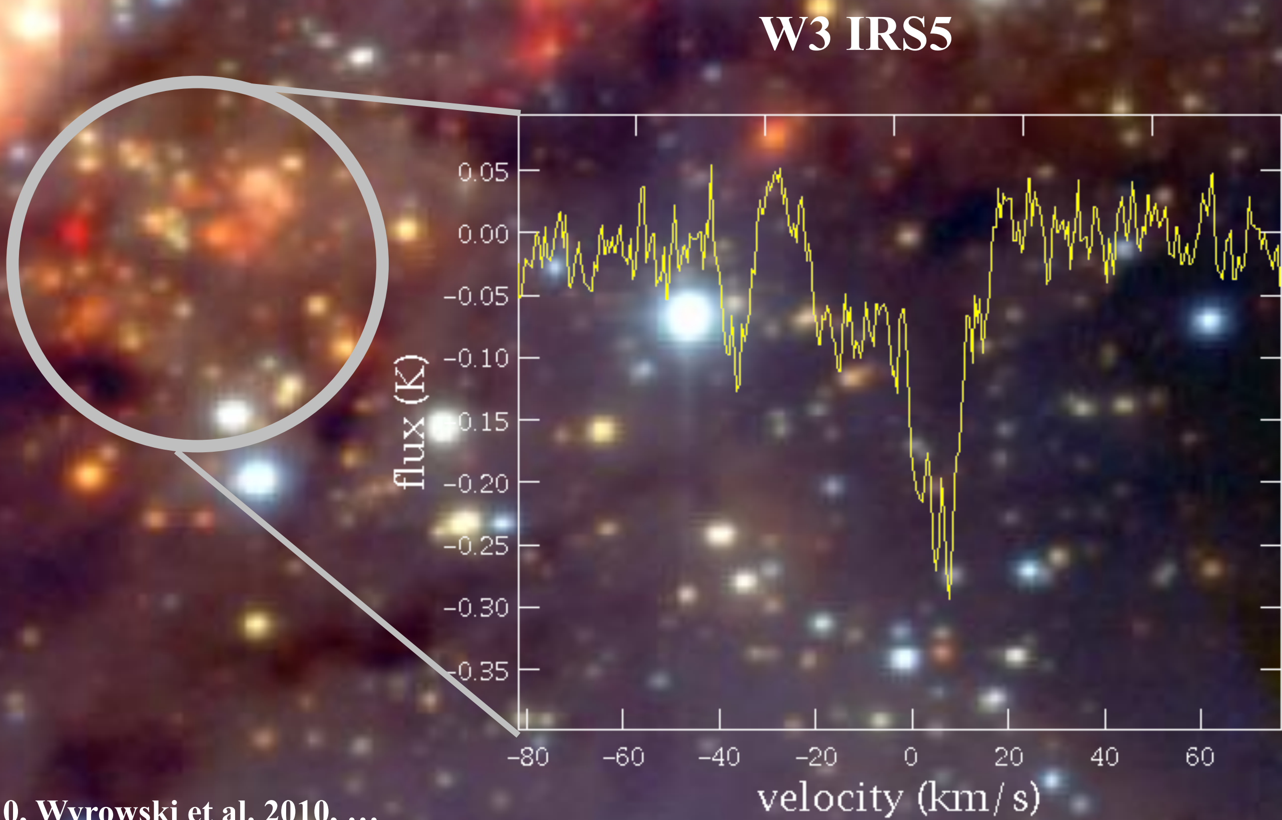
NGC 1333 IRAS4B
Plateau de Bure

$H_2{}^{18}O$ 3_{13}-2_{20} 203 GHz

Jørgensen & vD 2010

HDO/H_2O<6x10-4 in hot gas from interferometer data: Jorgensen et al. 2010, to be subm
50-100 times higher spatial resolution than Herschel

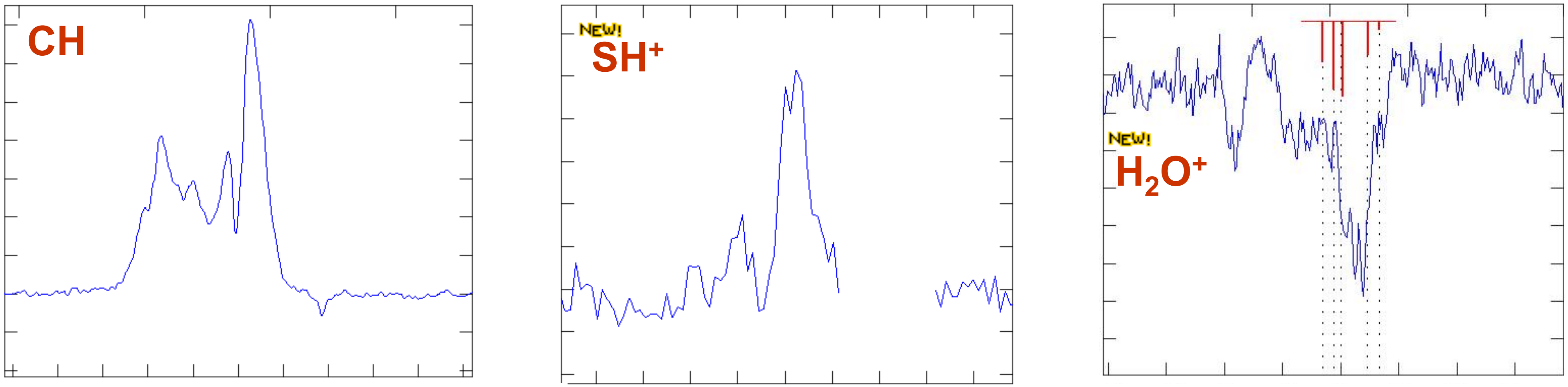
Surprise:
H_2O^+ widespread: the fourth 'phase' of water



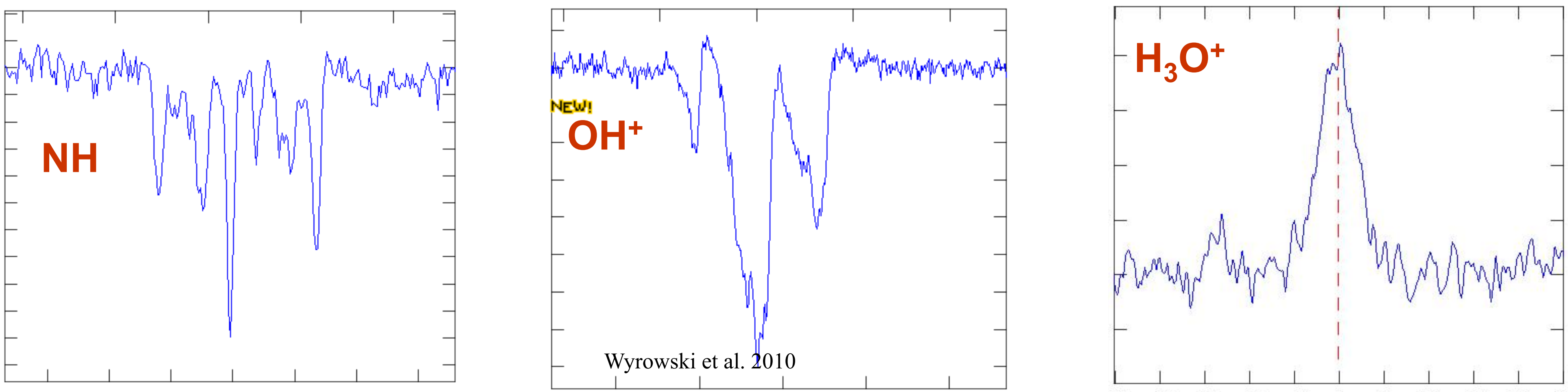
Benz, Bruderer et al. 2010

Also: Gerin et al. 2010, Ossenkopf et al. 2010, Wyrowski et al. 2010, …

Hydrides in Star Forming Region W3 IRS5



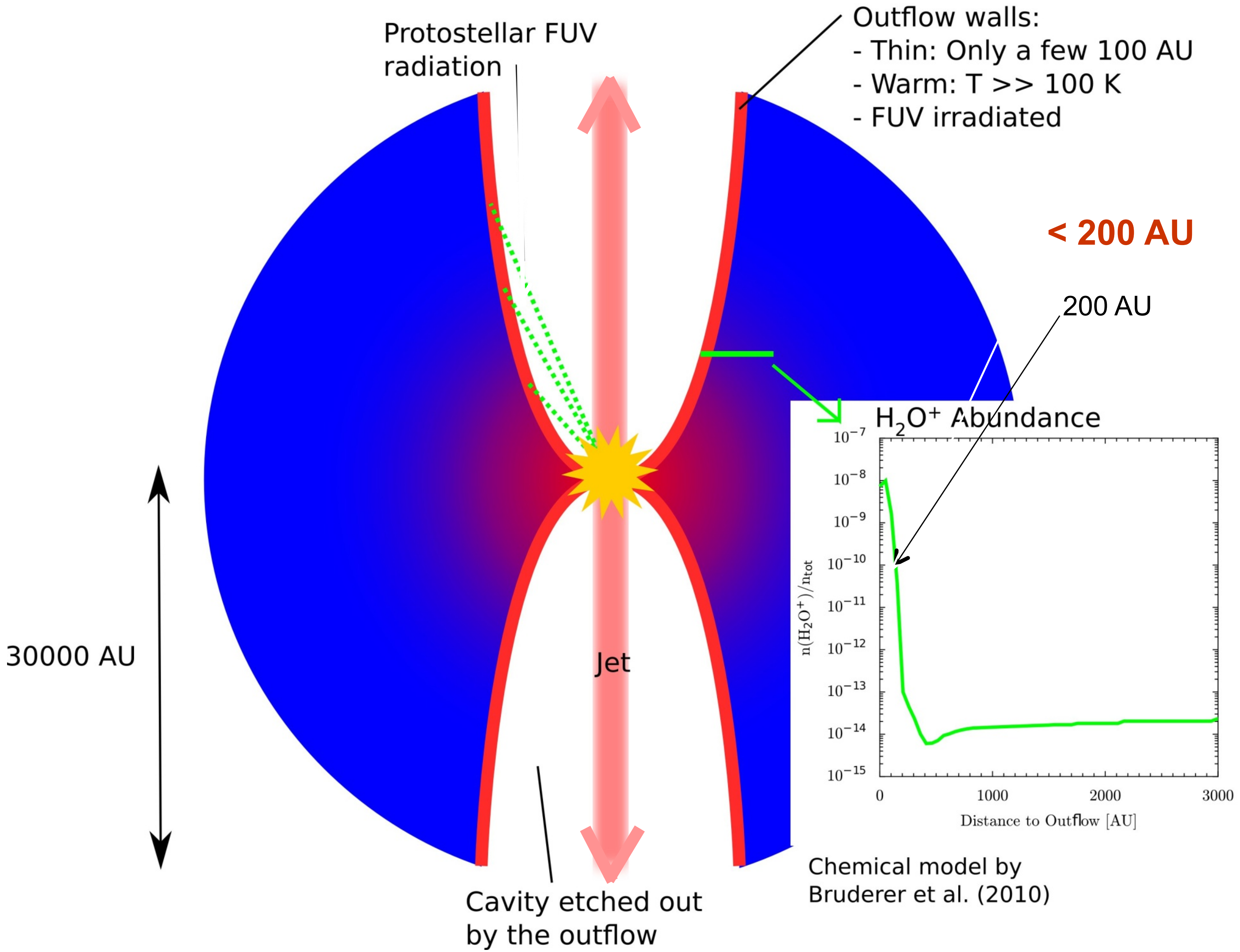
Menten et al. 2010



Dense gas: Diagnostics of UV (+ X-rays) heated outflow walls

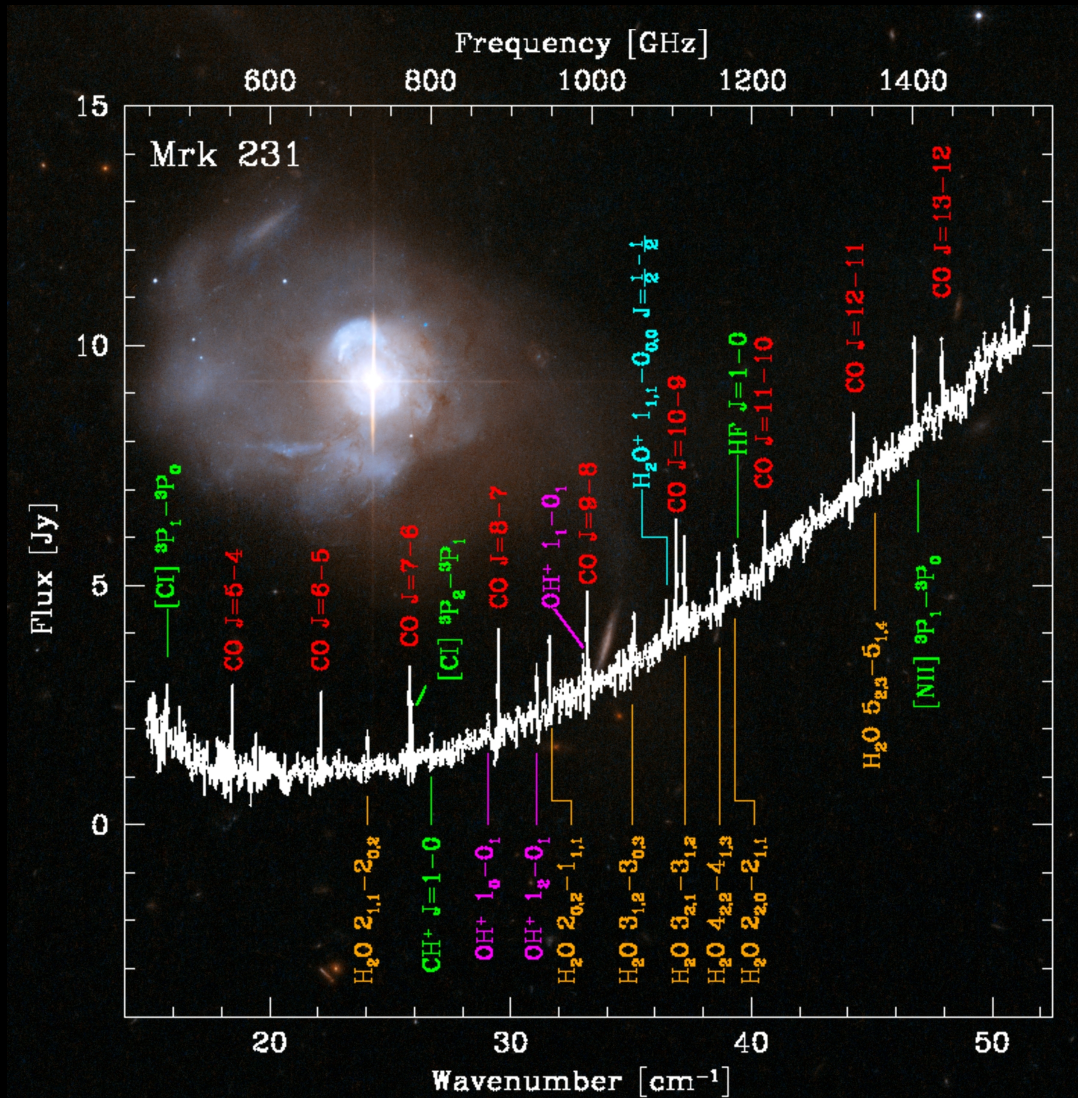
Diffuse gas: Warm gas with low H_2/H ratio

Benz et al. 2010



H_2O^+, OH^+, CH^+, and SH^+ are the paint on the outflow wall

Ionized water in galaxies



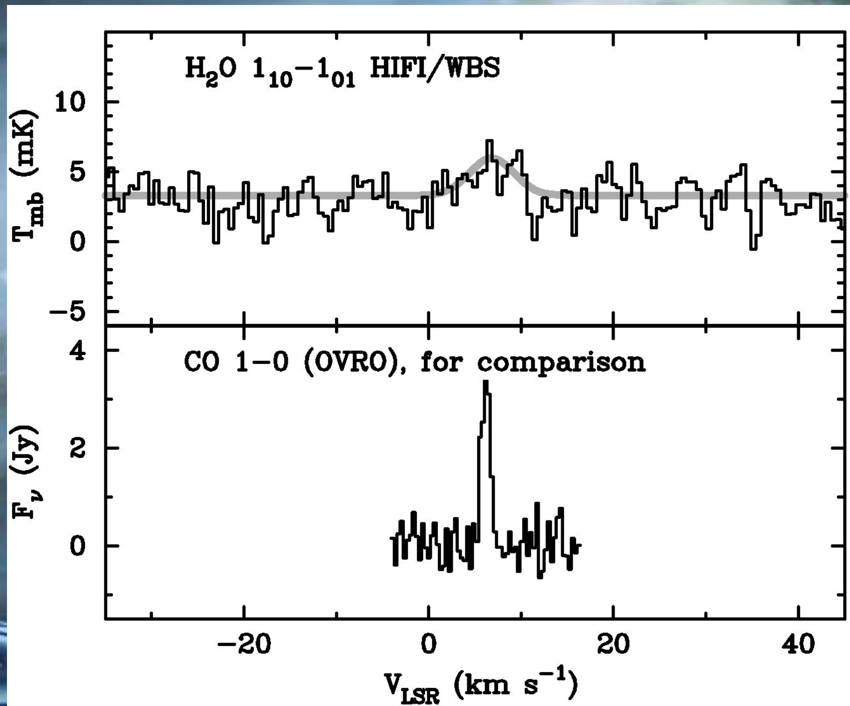
SPIRE-FTS

New, H_2 poor phase of the ISM?

Van der Werf et al. 2010

Protoplanetary disks
probing the cool water reservoir

limit few mK:
disk averaged
H_2O abundance
few x 10^{-10}



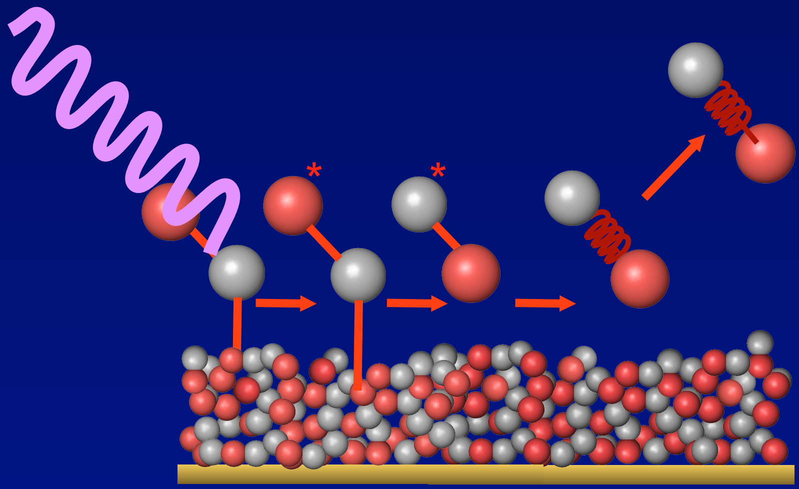
- Low limits indicate that icy grains have grown and settled to the disk midplane (⇒ assist planet formation)

- Grains in upper disk layers are ‘dry’ (bare silicates)

Bergin, Hogerheijde
+ WISH team 2010

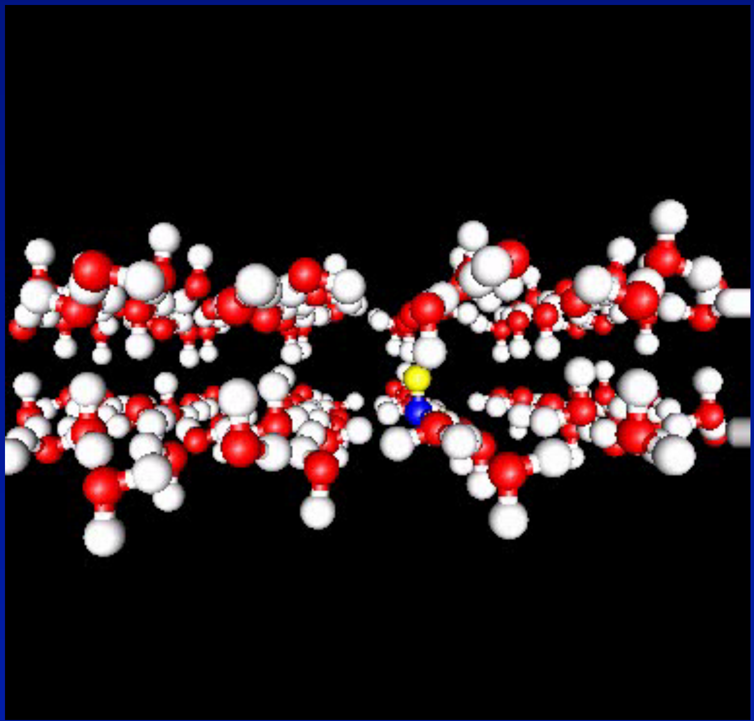
Importance of photodesorption

- **Typical efficiencies of 10^{-3} per incident photon**



Öberg et al. 2007, 2009.

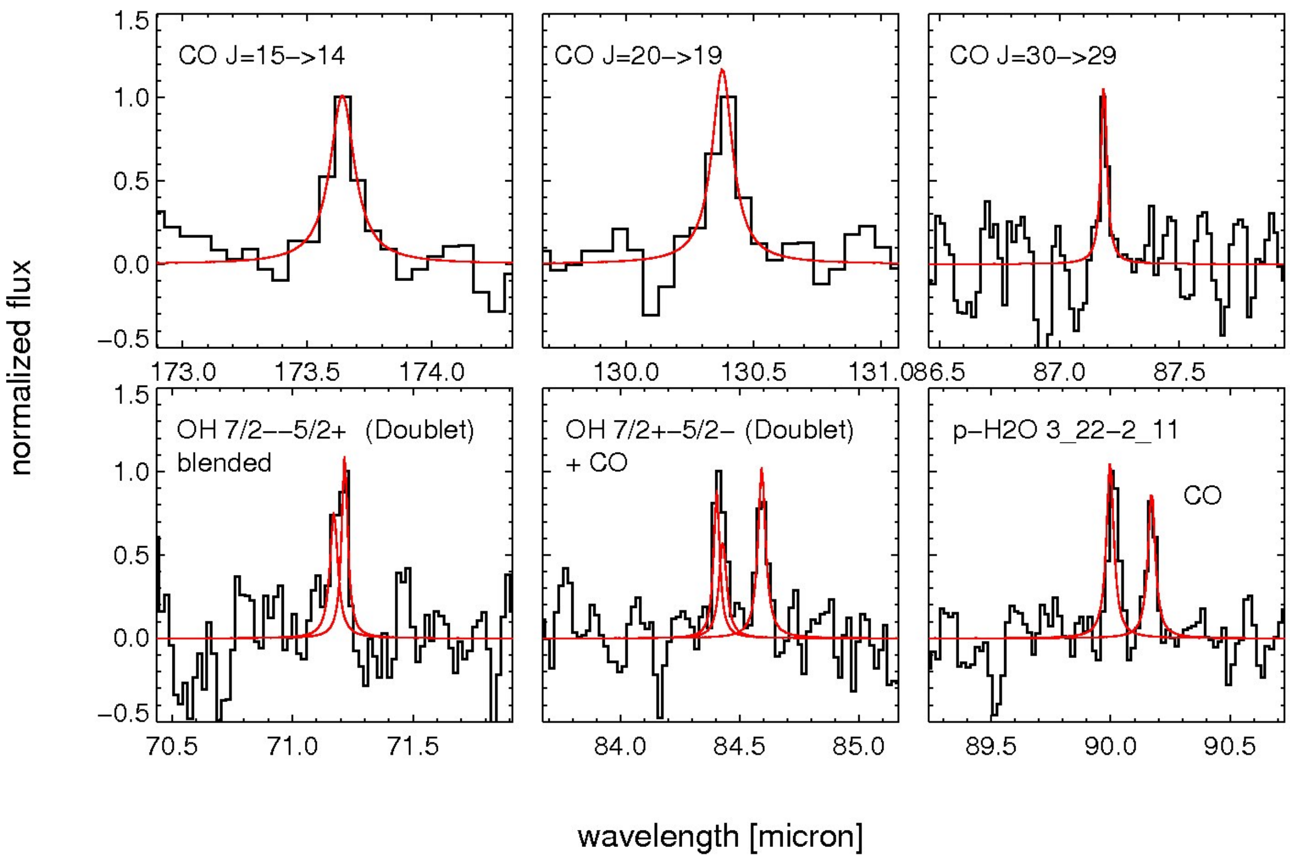
Direct vs kick-out mechanism



Andersson et al. 2006, 2008
Arasa et al. 2010

Warm water in inner disk

HD 100546 disk: PACS-DIGIT (~10-20 AU)



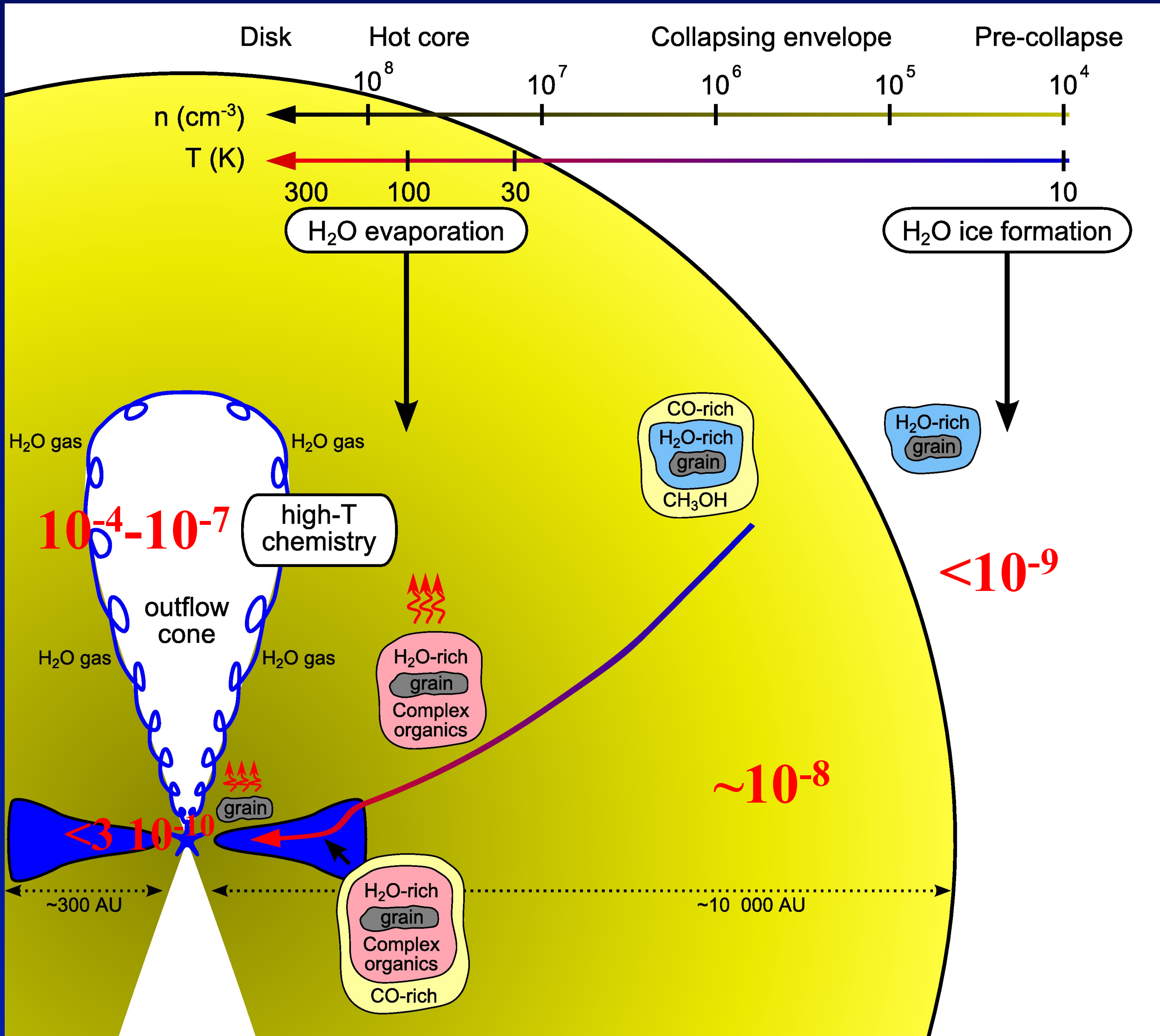
Sturm + DIGIT team 2010

Spitzer **(~1 AU): Salyk et al. 2008, Carr & Najita 2008, Pontoppidan et al. 2010**

Conclusions

- Herschel and HIFI work great!
- Gaseous water abundance in cold regions is very low
  - Lower than thought before (unless ‘dark’)
  - Water (vapor) is *not* everywhere!
- Warm CO and H_2O emission is dominated by shocks + UV photon heated component along outflow walls
  - Hot core emission difficult to detect
- Herschel CO and H_2O lines require models beyond spherical symmetry
- Ionized water H_2O^+ and related hydrides ubiquitous
- Water in outer disks on icy grains in midplane?

Where is water in protostellar envelopes?



All numbers preliminary